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THE ATMOSPHERE OF THE PLANET JUPITER

by V. G. Teyfel'

"Nauka" Press, Moscow, 1969

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THE ATMOSPHERE OF THE PLANET JUPITER

V. G. Teyfel'

ABSTRACT. This book is the first monograph in world astronomical literature devoted to the nature of the atmosphere of Jupiter, a typical representative of the group of giant planets. The book contains the results of optical and radiometric observations of Jupiter and gives a theoretical interpretation of these results. The structure and chemical composition of the atmosphere, the temperature conditions of the planet, the cloud cover of Jupiter, the circulation and active processes in the atmosphere are examined. This publication is intended for astronomers, specialists and qualified amateurs in astronomy. There are 27 tables, 215 bibliographical references and 73 illustrations included.

Editor-in-Chief, Candidate of Physical-Mathematical Sciences
V. A. Bronshten

Dedicated in Fond Memory of Vsevolod
Vasil'yevich Sharonov--An Outstanding
Investigator of the Planets

Introduction

Due to the utilization during the last decades of modern methods of astrophysical observations, including balloon observations and those conducted outside the atmosphere, a great quantity of valuable information concerning physical conditions on the planets of the solar system has been accumulated which surpasses all that has been amassed by researchers during at least the entire preceding century-long period of planetary study. The volume of our information concerning Jupiter, the largest and most characteristic representative of the group of giant planets, has increased significantly. Nevertheless up to the present time the nature of this planet continues to remain a riddle. The reasons for the turbulent activity in the atmosphere of Jupiter, which is almost 800 million kilometers from the sun, are not known. Only the approximate chemical composition of the atmosphere is known and the same situation obtains with respect to the structure of the atmosphere. In fact the physical nature of the planetary cloud cover, in which distinct, bright and colorful changes are observed, is not known. There is a basis for assuming the presence on Jupiter of internal sources of thermal energy but the nature of these is also not clear. The theory of circulatory processes in the atmosphere of Jupiter has not been developed and even the atmospheric phenomena /5* already observed on Venus have been insufficiently studied. Conclusive explanations have not been obtained for such formations on the planet as the Red Spot, or for such Jovian characteristics as non-thermal radio frequency radiation, zonality of rotation of the cloud cover and for many other properties.

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*Numbers in the margin indicate pagination in the foreign text.

This far from complete list of unsolved problems which are associated with Jupiter indicates the unquestionable need for a great deal of work in the future in the study of this planet. In contrast to the planets which are closer to us, we cannot even pin our hopes during the forthcoming 5-10 years, at the least, on solving many problems in the physics of Jupiter and of the other giant planets by means of space investigations. Undoubtedly the employment of space probes will permit us to obtain very valuable information concerning Jupiter in those optical, thermal and radio frequency radiation bands which are inaccessible during observations through the earth atmosphere. Nevertheless, the basic role in investigations of Jupiter for a long time to come will belong to ground observatories. /6

A great many articles have appeared in recent years devoted to individual, particular problems in observational and theoretical investigations of Jupiter. These works have thus far not solved a single problem pertaining to the physical nature of Jupiter but they present interest as fully definitive steps toward the solution of certain problems since they contain either new factual data or descriptions of new methods. Practically all observational results pertain to the external layers of Jupiter, or more exactly, to the external layers of its atmosphere. The internal structure of Jupiter is still an area of hypothesis and purely theoretical postulations. Since a great part of the work on the physics of the atmosphere of Jupiter has appeared in various foreign publications it seems to be advisable to present at least a short survey of these in the Russian language; in addition, insofar as the author is aware there are in existence in world astronomical literature only two monographs devoted to Jupiter: these include the monograph of V. G. Fesenkov, published in 1917 and Peek's book, published in London in 1958, which contains mainly the results of amateur visual observations.

In 1967, after the manuscript for this small monograph being offered for the readers attention had already been finished and delivered to the publisher, two new books appeared: "Reference Book on the Physical Properties of Jupiter," published in the U.S.A. under the editorship of Mihau, and the excellent book of V. I. Moroz, Fizika Planet,* in which a great deal of attention is devoted to the technique and contemporary results of optical and radio astronomical investigations of Jupiter.

Here, as apparent from the name of the book, we shall examine only problems associated with the atmosphere of Jupiter--mainly the results of optical and radiometric observations.

We shall touch upon the radio-frequency radiation of Jupiter only in connection with measurements of planetary temperature. Radio astronomical problems of Jupiter have been interpreted in sufficient detail in our literature

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including in particular the extensive monograph of V. V. Zheleznyakov, Radioizlucheniye Solntsa i Planet.

By atmosphere we usually mean the gaseous envelope which surrounds a planet. The upper limit of the atmosphere may be defined only conditionally, since the density of the atmosphere gradually decreases with altitude to the density of the interplanetary medium, then the lower limit is quite definite--it is the solid surface of the planet. The difference in densities between the atmosphere and the external layers of the planet itself for the earth and for planets of the earth group is very great; it is of approximately three orders /7 of magnitude. Thus, for example, the density of the earth core is 2.60 g/cm^3, whereas the density of the atmosphere near the surface of the earth equals $1.22 \cdot 10^{-3}$ g/cm^3. The chemical composition of the atmosphere also differs fundamentally from the composition of the core and the mantle of planets of the earth type.

On Jupiter and on other giant planets the situation is somewhat different. The equatorial diameter of Jupiter, according to average data cited in a summary of planetary characteristics compiled by S. V. Kozlovskaya [1], equals $D^{e}_{♃} = 142{,}470 \pm 200$ km $= 11.18 \pm 0.02$ of the earth. The polar diameter $D^{p}_{♃} =$ $= 133{,}160 \pm 200$ km $= 10.45 \pm 0.02\ D_{\oplus}$, and therefore the flattening of Jupiter $\varepsilon = (D^{e} - D^{p})/D^{e} = 1{:}15.3 = 0.065$. The magnitude of the flattening for Jupiter is somewhat greater than for the almost spherical planets of the earth group (for earth $\varepsilon = 0.003$ and for Mars $\varepsilon = 0.005$). If the volume of Jupiter surpasses that of earth by 1,308 times, then the mass, although large in absolute value, surpasses the mass of earth by only 317.38 ± 0.02 times. Thus the mean density of Jupiter, obtained by dividing the mass by the volume of the planet proves to equal 1.34 ± 0.01 g/cm^3. This is 0.25 of the mean density of the earth. Knowing the mass and the radius of the planet it is not difficult to find also the acceleration of gravity on the surface. On Jupiter the mean $g_{♃} = 2{,}600$ cm/sec^2 $= 2.65\ g_{\oplus}$. Since Jupiter rotates rapidly on its axis (the rotation period of the equatorial zone is $9^{h}50^{m}30^{s}$, but the rotation period of temperate zones of the planetary cloud layer, beginning with latitude $\phi > 12°$, is $9^{h}55^{m}10^{s}$), in the equatorial zone the acceleration of gravity is less than the value indicated above by 9%. The values cited pertain to the visible surface of the cloud layer.

An important circumstance, closely associated with these numerical characteristics of the basic peculiarities of Jupiter, is the fact that between the atmosphere and the solid mantle of Jupiter there is no sharp difference either in density or in chemical composition, which is characteristic of planets of the earth group. In fact it is still not known up to the present time whether Jupiter has a solid or a semi-liquid surface. The increase in pressure and density with depth in its atmosphere occurs until the basic components of the atmosphere pass from the gaseous phase to the liquid or the solid phase. The boundary region between the atmosphere and the surface of the planet itself is, in all probability, a zone of phase transformation in which a fundamental change in the chemical composition of matter does not occur. This means that for Jupiter, just as for the other giant planets, the atmosphere is simply an external planetary layer, or at least a dense envelope which consists mainly of the lightest elements, just as do the deeper layers. Of course the quantitative relationship between these elements (which apparently are mainly hydrogen and helium) in the atmosphere in the solid phase may be dissimilar.

It has already been indicated above that practically all observational information concerning Jupiter pertains to the outermost layers of its atmosphere. /8 Deeper layers of the atmosphere and the planetary surface are thus far completely inaccessible for observations. This significantly complicates the solution of the problem of the physical nature of Jupiter. We must form a concept of what occurs in the depths of this planet according to those phenomena which occur on the visible surface of the cloud cover of Jupiter and in the atmospheric zone above the clouds. It is completely obvious that in investigations of Jupiter the efforts of astrophysicists and observers alone are insufficient. The problems of the study of this planet demand the most active participation of specialists in the fields of radio astronomy, atmospheric physics, hydrodynamics, physical chemistry and solid state physics.

CHAPTER I

CHEMICAL COMPOSITION

§1. The Chemical Composition of the Atmosphere According to Spectral Observations.

a) The intensity of molecular absorption bands. We may obtain information /9 concerning the qualitative and quantitative composition of the planetary atmosphere by investigating spectrograms of the planet. If the planet is observed close to opposition, the sun's rays which are reflected from any point on the disk pass through a two-fold optical thickness of the atmosphere which lies above the visible surface of the planet (Figure 1). In this connection absorption lines and bands appear in the planetary spectrum which are created by the molecules which enter into the composition of the atmosphere of gases. The intensity of planetary radiation in the absorption band will be determined by the expression

$$I_{ab}(\lambda) = I_{co}(\lambda)\, e^{-2\tau_{ab}(\lambda)/\eta}, \tag{1.1}$$

where I_{co} is the intensity of radiation falling upon the planetary atmosphere in the continuous spectrum; τ_{ab} is the optical thickness of the atmosphere in the absorption band; $\eta = \cos \vartheta$[1]. Total absorption in the band equals

$$W = \int_0^\infty \left[1 - \frac{I_{ab}(\lambda)}{I_{ab}(\lambda)}\right] d\lambda \tag{1.2}$$

and depends on the value of the absorption coefficient in the given band and on the number of absorbent molecules, i.e., on the absolute content of the gas investigated in the planetary atmosphere. Total absorption is associated with the number of molecules in a different manner, depending on the optical mass of the absorbent gas layer. With small masses $k_0 m = k_0 N\mu$ (N is the number of molecules, k_0 is the maximum absorption coefficient in the center of the absorption line; μ is the molecular weight) and correspondingly small values for the auxiliary input value $u = k_0 m/2$, the theoretical derivation of the formula for total absorption leads to the expression

$$W = \frac{1}{a}\left(\pi - \frac{2}{a}\right) u - \frac{1}{2a}\left(\pi - \frac{4}{3a}\right) u^2 + \cdots \tag{1.3}$$ /10

---

[1] At angles ϑ, close to $\pi/2$, the I_{ab} (λ) dependence on ϑ proves to be more complex than exp $[-2\tau_{ab}(\lambda)/\cos \vartheta]$.

or, if we disregard all terms of the expansion except the first,

$$W = \frac{1}{a}\left(\pi - \frac{2}{a}\right)u, \tag{1.4}$$

where value a is determined by the limits of integration of intensities for a given absorption line or band. It is clear that in this case

$$W \sim N. \tag{1.5}$$

If the optical mass of the gas or the optical path length of light in the absorbent layer is great, then

$$W = 1 - \frac{3}{2}\,\frac{e^{-2u/a^2}}{2u/a^2} - \frac{\sqrt{\frac{2\pi u}{a^2}}}{8u} + \cdots \tag{1.6}$$

or after certain simplifications

$$W = \sqrt{\frac{2\pi u}{a^2}}, \tag{1.7}$$

i.e.,

$$W \sim \sqrt{N}. \tag{1.8}$$

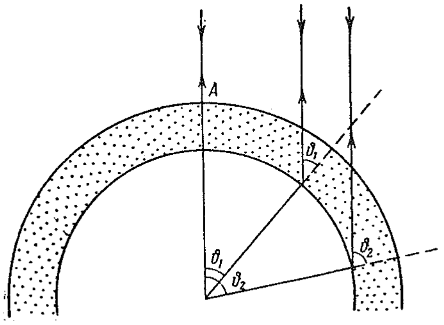

Figure 1. The Transmission of Incident and Reflected Rays through the Planetary Atmosphere.

In measurements of the absorption bands in the integral spectrum of the entire planetary disk it is necessary to consider the circumstance that the absorption observed corresponds to a certain mean optical length of the path of the ray in the atmosphere, equal to $4\tau_{ab}$, if darkening toward the limb of the planetary disk is lacking, and $3\tau_{ab}$ if the limb of the disk is completely dark. Since Jupiter displays a noticeable drop in brightness toward the edges of the disk, the value of the mean length of the optical path of light should lie between these values [3, 4]. However, it will be apparent from further discussion that the actual value of the mean optical path which corresponds to the observed intensity of the absorption bands on Jupiter proves to be completely different.

/11

This is associated with the fact that a change in the intensity of the absorption bands from the center of the Jovian disk to the limbs does not correspond to equation (1.1). Therefore it is not possible to transform the absorption band intensities obtained from the integral spectrum of Jupiter into the optical thickness of the atmosphere or to compare these intensities directly with the intensities of the same bands in laboratory spectra of corresponding gases. A comparison of planetary and laboratory spectra of molecular absorption, without which it is not possible to determine the quantitative content of gas in the planetary atmosphere, it is also difficult for other reasons, but in any case quantitative measurements will be more reliable if only the spectrum of the central zone of the Jovian disk is examined. Unfortunately in the infrared region of the spectrum (with $\lambda\lambda > 1\ \mu$), where the most intense absorption bands are located, measurements are accomplished only for the entire Jovian disk as a whole, and absorption variation over the disk thus far remains unknown.

b) The identification of absorption bands in the spectrum of Jupiter. The first photographic investigations of the spectrum of Jupiter were accomplished by V. Slipher [5,6] who detected a whole series of absorption bands in the visible and in the near-infrared region. Several of these bands were identified by R. Wildt [7] with the laboratory spectrum of ammonia (NH_3). It was found that those bands attributed to ammonia and which display maximum intensity in the spectrum of Jupiter are very few in the spectrum of Saturn[1] and are absent in the spectra of Uranus and Neptune; this is in contrast to other more numerous bands, the intensities of which, on the other hand, increase with the transition from Jupiter to Neptune. Wildt expressed the proposal that these latter bands may be caused by the presence of methane (CH_4) in the atmospheres of the giant planet, which was soon confirmed by A. Adel and V. Slipher [8] who compared the spectra of the giant planets with laboratory spectra of methane.

Methane and ammonia absorption bands observed in the visible and in the near-infrared range represent overtones and combined bands which correspond to different combinations of the basic (fundamental) frequencies of the vibrations of the CH_4 molecules ($\nu_1 = 2915$ cm^{-1}, $\nu_2 = 1520$ cm^{-1}, $\nu_3 = 3020$ cm^{-1}, $\nu_4 = 1306$ cm^{-1}) and the NH_3 molecules ($\nu_1 = 3337$ cm^{-1}, $\nu_2 = 3415$ cm^{-1}, $\nu_3 = 933$ and 967 cm^{-1}, $\nu_4 = 1628$ cm^{-1}).

Table 1.1 shows frequencies and wave lengths for methane absorption bands in the spectrum of Jupiter in agreement with the identification made by Adel and Slipher. The symmetrical fundamental vibrations ν_1 and ν_2 are not active optically since they are not accompanied by changes in the electrical moment of the molecule. Therefore vibrations ν_3 and ν_4, as well as their /12 overtones and component frequencies are manifest in the absorption. Selection rules prohibit the appearance in the infrared spectra of absorption bands with frequencies $n\nu_1 + m\nu_2$ (n and m are integrals beginning with zero). The lack of these bands significantly simplifies observation of the methane spectrum for the giant planet.

---

[1] In 1965 T. Owen [56] showed that ammonia bands are lacking in the spectrum of Saturn.

TABLE 1.1. CH_4 ABSORPTION BANDS IN THE SPECTRUM OF JUPITER

λ, Å	Frequency	λ, Å	Frequency	λ, Å	Frequency	λ, Å	Frequency
5430	$7\nu_3$	7200	$11\nu_4$	8020	$5\nu_3 - \nu_4$	8860	$4\nu_3$
5760	$6\nu_3 + \nu_4$	7250	$5\nu_3$	8160	$5\nu_3 - \nu_2$	9420	$6\nu_4 + \nu_3$
6190	$6\nu_3$	7820	$4\nu_3 + \nu_2$	8430	$7\nu_4 + \nu_3$	9800	$8\nu_3$
6680	$5\nu_3 + \nu_1$	7880	$10\nu_4$	8610	$3\nu_3 + \nu_1$	9870	$3\nu_3 + \nu_2$
7020	$4\nu_3 + \nu_1$	7980	$4\nu_3 + \nu_4$	8740	$9\nu_4$	10090	$3\nu_3 + \nu_4$

At the same time the tetrahedral form of the methane molecule creates a rather complex, fine structure of rotational bands. The investigations of D. Dennison and S. Ingram [10] reveal that the vibrational energy levels $n\nu_3$ are multiplets, and the difference in the frequencies of the multiplets are small in comparison with the fundamental frequency; intrinsically it is of the same order as the rotational structure of the bands. Thus if we deal with a harmonic of the n-th order, then approximately 1/4 (n + 1)(n + 2) of the bands overlap each other while forming a complex single band $n\nu_3$. Thus, for example, the band $7\nu_3$ (5430 Å) actually represents the result of the overlapping of approximately 18 bands. Therefore these bands are very difficult to resolve. Since we shall not discuss these problems in detail, we refer the reader to appropriate monographs on molecular spectra [11-14]. We shall point out only that the frequency interpretation of the methane bands given in Table 1.1 is not unique; the fundamental frequencies ν_1 and ν_3 are very close to each other and the frequency $2\nu_2$ almost coincides with them. As a result, as noted by N. Bobrovnikoff [9], K. Kiess and C. Corliss [15], component frequencies $n\nu_1 + m\nu_3$ lie very close to $(n + m)\nu_3$, but frequencies $2k\nu_2 + m\nu_3$ are close to $(k + m)\nu_3$. The overlapping bands hinder exact measurement of wave lengths of their centers, which also leads to a certain vagueness in interpretation.

In the absorption bands of ammonia in the visible and in the near-infrared range of the spectrum of Jupiter (Table 1.2), only the NH_3 bands, 6430 and /13
7928 Å, are easily detected, whereas the remaining blend together to a greater extent than the more intensive methane bands. Recently still another NH_3 band was discovered [16] in the spectrum of Jupiter with a center at λ 7654 Å--in the vicinity of the telluric band A, which consists of a set of weak lines in the interval λλ 7561-7763 Å.

TABLE 1.2. NH_3 ABSORPTION BANDS IN THE SPECTRUM OF JUPITER

λ, A	Frequency	λ, A	Frequency
5490	—	8910	$3\nu_1 + \nu_2$
6430	$5\nu_1\ (4\nu_1 + \nu_2)$	9900	$\nu_1 + 2\nu_2$
7930	$4\nu_1\ (2\nu_1 + 2\nu_2)$		

Intensive methane and ammonia absorption bands are present in the far-infrared region of the spectrum. A list of these is contained in Tables 1.3 and 1.4 according to observational data of V. I. Moroz [17], and a frequency interpretation made by G. Herzberg [12].

TABLE 1.3. CH_4 BANDS IN THE INFRARED SPECTRUM OF JUPITER

λ, μ	Frequency	λ, μ	Frequency
1.00	$2\nu_1 + \nu_2 + \nu_3,\ \nu_1 + \nu_2 + 2\nu_3$	1.72	$\nu_1 + \nu_2 + \nu_4,\ \nu_2 + \nu_3 + \nu_4$
1.12	$2\nu_1 + \nu_3,\ \nu_1 + 2\nu_3;\ 3\nu_3$	2.20	$\nu_2 + \nu_3$
1.19	$2\nu_1 + 2\nu_4,\ 2\nu_3 + 2\nu_4$	2.32	$\nu_3 + \nu_4$
1.33	$\nu_2 + 2\nu_3$	2.38	$\nu_1 + \nu_4$
1.67	$2\nu_3$	2.42	$\nu_2 + 2\nu_4$

TABLE 1.4. NH_3 BANDS IN THE INFRARED SPECTRUM OF JUPITER

λ, μ	Frequency	λ, μ	Frequency
1.52	$2\nu_1,\ 2\nu_3,\ \nu_1 + \nu_3$	2.23	$\nu_2 + \nu_3$
1.67	$\nu_2 + \nu_3 + \nu_4$	2.33	$\nu_1 + \nu_2$
1.98	$\nu_3 + \nu_4$		

The infrared spectrum of Jupiter in the range 0.8-3.1 μ, free of telluric /14
water vapor absorption bands, was studied by R. Danielson [74] with four recordings obtained by means of an infrared spectrometer which was installed on the balloon telescope "Stratoscope II" during the night of 26-27 November 1963. Figure 2 shows one of these recordings reduced to the level of the continuous spectrum which corresponds to the brightness of a matte screen with an albedo

of 0.5 situated at a Jovian separation normal to the suns rays. The arrows denote CH_4 and NH_3 bands which were observed in laboratory spectra.

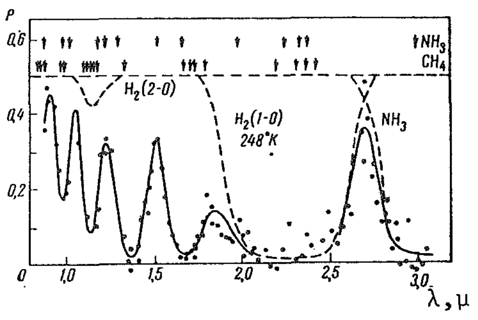

Figure 2. A Recording of the Infrared Spectrum of Jupiter With the Methane, Ammonia and Hydrogen Absorption Bands Identified (According to Danielson).

For a long time methane and ammonia were considered to be the only gases whose presence in the atmosphere of Jupiter had been confirmed by direct observations. Only indirect considerations (the low mean density of Jupiter, the presence on the planet of hydrogen compounds) formed a basis for assuming the existence of a Jovian atmosphere consisting mainly of light gases in which methane and ammonia were only admixtures. It was only in 1957 that the presence on Jupiter of molecular hydrogen [15] was established through spectroscopic observations which resulted in a quadrupole vibration-rotation band near λ 8200 Å. This band was investigated in the laboratory and was later detected in the spectra of Uranus and Neptune by G. Herzberg [19]. The lines of this band in the spectrum of Jupiter practically coincided with the laboratory lines (Table 1.5).

TABLE 1.5. QUADRUPOLE BAND LINES (3,0) OF MOLECULAR HYDROGEN

Spectrum of Jupiter λ,Å	Laboratory Spectrum, λ,Å	Designation	Spectrum of Jupiter λ,Å	Laboratory Spectrum, λ,Å	Designation
8497,52	8497;49	Q (1)	8150,66	8150,68	S (1)
8272,60	8272,69	S (0)	8046,44	8046,44	S (2)

Tr. Note: Commas indicate decimal points.

Intense absorption in the region 2.0-2.5 μ (see Figure 2) corresponds to the absorption band (1,0) of molecular hydrogen. The presence itself of quadrupole H_2 absorption bands in the spectrum of Jupiter indicates that hydrogen must be present in the Jovian atmosphere in large quantity. /15

c) Quantitative spectrum evaluations of gas content. In the case of Jupiter, a determination of the gas content in the planetary atmosphere, made by comparing observational and laboratory intensities of absorption bands, proves to be quite unreliable.

The reference data employed for methane and ammonia are based exclusively on evaluations by G. Kuiper, who compared spectrograms of Jupiter and spectrograms of CH_4 and NH_3 obtained in the laboratory by means of a large absorption column with multiple light-ray passage [4]. Kuiper himself noted that his evaluations were preliminary both in view of difficulties involved in the interpretation of the optical path length of the light ray in the planetary atmosphere as well as in connection with the fact that the intensity distribution observed in absorption bands of laboratory and planetary spectra obtained were quite different. The latter may have been caused by a large difference in gas temperatures in the laboratory and in the planetary atmosphere.

According to Kuiper the atmosphere of Jupiter above the clouds contains a quantity of methane which is equivalent to a layer of this gas 15,000 cm in thickness at standard temperature and pressure. T. Dunham [20] estimated the ammonia content according to the absorption band λ 6430 Å at 500-1000 cm under standard conditions. Subsequently Kuiper found that the NH_3 content equaled 700 cm-atm. These values are also utilized now in practically all calculations without the critical evaluation which is urgently required. The fact is that the absorption observed in molecular bands in the spectrum of Jupiter is usually attributed only to that part of the atmosphere above the clouds, and the cloud layer is considered to be completely non-transparent and only a reflector of solar rays. Actually, as shown by theoretical calculations and observations of molecular absorption in earth clouds, under certain conditions basic molecular absorption may occur within the cloud layer in the process of the multiple scattering of light on aerosols, rather than in the atmosphere above the clouds.

V. I. Moroz [215] even without considering the role of multiple scattering, expressed the opinion that the estimate of CH_4 content obtained by Kuiper should be reduced by approximately two times, and thus the contents would equal ~7500 cm-atm.

In comparing spectrograms of Jupiter and new laboratory spectra of methane, obtained at the Jet Propulsion Laboratory (U.S.A.), J. Beckman [206] also found that the CH_4 content must be approximately 10,000 cm-atm.

A quantitative evaluation of the ammonia content in the atmosphere of Jupiter was accomplished recently by V. I. Moroz [17], who compared the intensity of the NH_3 1.51 μ band with laboratory data of R. Robertson and J. Fox [21] and obtained a value of 40-50 cm-atm. This is one order of magnitude less than the quantity of NH_3 estimated according to the band λ 6430 Å. Since V. I. Moroz investigated the spectrum of the entire disk of Jupiter, in order to interpret this result, it is necessary to know the distribution of the ammonia absorption over the Jovian disk in the 1.51 μ band. More than likely the reason for the contradiction obtained lies in the effect of multiple scattering and absorption in the cloud layer. Below we shall examine this effect in greater detail. /16

The determination of the quantitative content of hydrogen was made for the first time by F. Zabriskie [22] from the spectrograms of Kiess and Corliss. He obtained an equivalent thickness of the hydrogen layer $5 \cdot 10^5$ km-atm, i.e., 5 km-atm. H. Spinrad and L. Trafton [23], in comparing directly spectrograms of Jupiter and H_2 laboratory spectrograms, obtained a hydrogen content in the atmosphere of Jupiter of 27 ± 9 km-atm. J. Foltz and D. Rank [24], on the basis of calculations of the intensities of H_2 lines and of laboratory measurements, came to the conclusion that the previously stated estimates of hydrogen content represented reduced values and that they should be one order of magnitude higher, i.e., approximately 240 km-atm.

On the other hand T. Stecher recently published [25,26] the results of an investigation of the ultraviolet spectrum of Jupiter in the region λλ 2000-3000 Å according to observations from the high-altitude "Aerobee" rockets. Figure 3 shows the behavior of the geometrical albedo which he obtained in accordance with the spectrum in the ultraviolet (P) and theoretically calculated curves of the spectral reflectivity of the planet surrounded by a hydrogen atmosphere of given thickness. The calculation of 10.2 km-atm for H_2 content satisfies observations in the best way possible. Of course it is assumed here that the albedo for the visible surface of the planet is equal to zero. If the albedo for the cloud surface in the ultraviolet is taken as 0.25, then the total number of scattered atoms and molecules in the atmosphere above the clouds is decreased by 10 times and the P (λ) curve becomes almost neutral, which does /17
not correspond to observational data. Thus according to the ultraviolet spectrum of Jupiter it is as if the value 10.2 km-atm is the upper limit of the H_2 content in the Jovian atmosphere above the clouds.

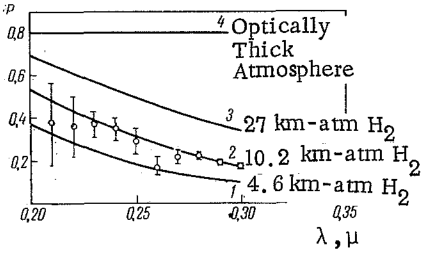

Figure 3. The Spectrum of Jupiter in the Region λλ 2000-3000 Å (According to Stecher).

Based on the intensity of lines S(1) and S(2) of the H_2 (3-0) quadrupole band, W. Tenaka [205] obtained 39 km-atm as the H_2 content above the cloud layer of Jupiter; subsequently, however, by means of a comparison with the empirical curve of growth for hydrogen quadrupole lines, he reevaluated this estimate and found the H_2 content to be 110 km-atm.

J. Beckman [206] notes that large values for the content of H_2 which exceed 100 km-atm do not agree with atmospheric pressure estimates since they lead to a pressure value on the surface of the cloud layer of more than 5 atm. This value contradicts measurements made by several investigators (see page 68).

In agreement with the approximate calculations of V. I. Moroz [208], according to the intensity of the H_2 absorption band induced by pressure in λ 1.97 μ, the H_2 content must be less than 45 km-atm.

We see that estimates of the quantity of molecular hydrogen on Jupiter are quite contradictory. The results of Danielson [74] also provide no definitive answers; in agreement with his results the hydrogen content in the infrared region of the spectrum according to the H_2 bands is ~45 km-atm. Here an excessively high temperature on the surface of the cloud layer of 200-225°K is assumed and the possible effects of scattering and absorption in the cloud layer are not considered.

§2. The Distribution of Molecular Absorption Intensity on the Jovian Disk.

a) Absorption in the outer atmosphere. During calculations of the quantitative content of hydrogen, methane and ammonia in the atmosphere of Jupiter a single-layer model of the absorbent atmosphere is usually employed in which the formation of absorbent bands occurs only in the pure gaseous layer above the clouds. Henceforth we shall call this layer the outer atmosphere of Jupiter. We shall assume that the cloud layer of the planet actually functions only as a reflecting non-transparent screen and does not participate in any way in the formation of planetary absorption lines and bands. Then at opposition, where the angles of incidence and reflection are equal, the residual intensity on any point of the absorption line or band, generated in the outer atmosphere, will equal

$$\frac{I_{ab\lambda}}{I_{co\lambda}} = e^{-2\tau_{ab\lambda}\sec\vartheta}, \qquad (1.9)$$

where $\tau_{ab\lambda}$ is the optical thickness of the outer atmosphere which changes, of /18 course, with wavelength. During the transition from the center to the limbs of the disk, i.e., with an increase in ϑ the residual intensity will decrease in all wavelengths of the band, i.e., the depth and total intensity of the absorption band will increase. If the total absorption is not too great, i.e., if the band is not saturated, then where $\vartheta = 60°$ ($\sec\vartheta = 2$) the absorption band intensity will be twice as high as in the center of the disk (Figure 4).

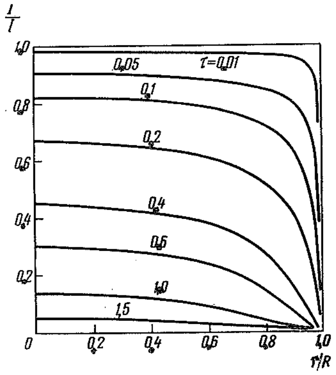

Figure 4. Molecular Absorption Behavior on the Planetary Disk Surrounded by an Atmosphere with Optical Thickness τ.

b) The results of observations. In fact absorption band intensification toward the limbs is not observed on the Jovian disk. There are available a comparatively large number of measurements of the intensity of the methane absorption band, especially of the band λ 6190 Å, accomplished by V. I. Yeropkin [27,28], N. Bobrovnikoff [29], C. Elvey and A. Fairley [30], S. Hess [31] and V. G. Teyfel' [32-35] for various regions on the Jovian disk. The weak CH_4 band 5430 Å [32,33] and the NH_3 band 6443 Å [31] have also been investigated. All of these investigations lead to the conclusion that absorption is not intensified toward the limbs of the disk. We shall examine for an example the band CH_4 6190 Å. This band has a residual intensity at the center $I_{ab}/I_{co} = 0.78$. Its fine structure was investigated by Kiess and Corliss [15] and according to their data consists of 24 resolvable lines. The lines merge in the center of the band even with great spectrograph dispersion. Subsequently the band structure in the spectra of Jupiter and Saturn was studied by H. Spinrad and L. Trafton [23], and in the laboratory spectrum by D. Phillips. Unfortunately there were no photometric evaluations of the intensity of individual lines in the band. However since the central depth of the band is not great the individual lines near the center of the band are hardly near saturation.

According to the author's observations in 1963 the intensity of the CH_4 absorption band (6190 Å) in various latitude zones of Jupiter was characterized by the following values of equivalent latitude (W_{ab}) and depth ($R_{ab} = 1 - I_{ab}/I_{co}$) (Table 1.6), which pertain to segments of the disk situated near /19
the central meridian.

TABLE 1.6. INTENSITY OF THE CH_4 BAND (6190 Å) IN VARIOUS ZONES OF THE JOVIAN DISK

Zone	Latitude, deg.		W_{ab}, Å	R_{ab}
	From	To		
	Southern Hemisphere			
Polar region	−50	−80	19,5	0,218
Temperate dark band	−20	−30	20,0	0,222
Tropical light band	−10	−20	18,5	0,212
Equatorial dark band	0	−10	20,4	0,231
	Northern Hemisphere			
Equatorial dark band	0	+15	20,4	0,229
Tropical light zone	+15	+25	19,1	0,217
Temperate light zone	+25	+35	18,6	0,215
Polar region	+50	+80	18,3	0,221

Tr note--commas denote decimal points.

It is apparent from the Table that total absorption in a band undergoes fluctuations within limits of 10% depending on position on the disk. In this connection an increase in W_{ab} toward the limbs of the disk is not detected. Moreover, measurements of the intensity of CH_4 infrared absorption bands in the region $\lambda\lambda$ 0.7-1.0 μ, conducted by the author in 1965 [36,37], reveal a decrease in methane absorption toward the limbs of the disk along the equator as well as along the central meridian.

The results of observations in recent years (1965-1967) obtained at the GAO AN USSR [Main Astronomical Observatory of the Academy of Sciences of the Ukrainian SSR] by V. V. Avramchuk [209] and at the Astronomical Institute of the Academy of Sciences of the Kazakh SSR by A. N. Aksenov and by the author for the CH_4 band (6190 Å) also clearly indicate the decrease in the intensity of this band toward the limbs of the disk of Jupiter by at least 30%. It is possible that the distribution along the Jovian disk is subject to temporary fluctuations but further systematic observations are required in order to verify this conclusion.

c) Interpretation of the results. S. Hess [31] attempted to explain the invariability of methane absorption along the Jovian equator by the fact that near the limbs of the disk the cloud layer is located at greater altitude than in the center of the disk, where due to evaporation of cloud particles the cloud boundary is reduced in altitude. Then near the limbs of the disk the vertical optical thickness of the outer atmosphere must be less while the product of $\tau_{ab}(\vartheta)$ sec ϑ, which determines absorption behavior along the disk in the single-layer model, must remain approximately constant for all points of the disk. According to Hess' calculations, the temperature on the morning limb of the Jovian disk must be 8-9°K lower and on the evening limb, approximately 4°K lower than at the center of the disk. /20

P. Squires [38] revealed, however, that the heat obtained from the sun by a segment of the cloud layer during the rotation of Jupiter by 60° (the transition from the morning limb to the sub-solar point) may be sufficient for the evaporation of not more than 0.01 g/cm^2 of condensed ammonia, while for the fulfillment of the conditions involved in Hess' hypothesis (a reduction in the height of the limit of the cloud layer toward the center of the disk by approximately 10 km) NH_3 evaporation is required of not less than 0.43 g/cm^2. If we consider that the cloud layer consists mainly of crystals or drops of ammonia, it is true that the required effect may be achieved if we accept an extremely low density for the dispersed phase, but even in this case the upper limit of the cloud layer could not rapidly increase toward the evening limb, since heating by solar rays does not cease after mid-day. Squires proposed another hypothesis in agreement with which at least the upper part of the cloud cover of Jupiter has a tower-shaped structures, i.e., consists of cloud elements similar to earth cumulus clouds, the tops of which are approximately 20-30 km above the basic cloud surface. Here the line of sight penetrates to the base of the clouds only near the center of the disk, but with an approach to the limb the effective depth of ray penetration decreases which also leads to a lack of intensification of molecular absorption at the limbs of the disk. In order to explain the effects observed, however, Squires had to assume the possibility of a change in the altitude of the upper cloud elements during the course of a day.

Notwithstanding the comparative simplicity of such an explanation for the absorption distribution observed on the Jovian disk, it is difficult to agree with it. The fact is that with a tower-resembling structure of the surface of the cloud cover the most effective influence of this structure on the value of the molecular absorption would occur during approximately equality of such structure parameters as altitude, width of the base of cloud elements and distance between them. But this would be unavoidably reflected in the value of darkening toward the limbs of the disk in the continuous spectrum. The darkening toward the limb observed on Jupiter, as we shall see below, satisfies comparatively well calculations for an even cloud layer surface. In the presence of a sharply expressed cloud surface structure darkening toward the limb would be considerably less or might even be lacking altogether.

The absence of molecular absorption intensification toward the limb of the disk is observed not only for Jupiter, but also for Saturn and Venus. Recently many authors (J. W. Chamberlain [47,48], G. V. Rosenberg [179], W. Irvine [46], etc.), in connection with spectral investigations of the chemical composition of planetary atmospheres, have directed their attention /21 to effects associated with molecular absorption in planetary cloud layers. As we shall see below these effects in particular may explain absorption behavior characteristics observed on planetary disks surrounded by atmospheres with a transparent cloud cover.

d) **Scattering and Absorption in the Cloud Layer.** We shall examine a Jovian cloud layer with a smooth upper limit. We shall arbitrarily assume that there is no atmosphere above the cloud layer. Here we shall deal with a turbid medium of very great optical thickness in which light scattering occurs mainly on cloud particles (aerosols) which also gives rise to a certain amount of true absorption and which is continually increasing in the direction of short wavelengths. These particles are suspended in a gas or in a mixture of gases which absorb light in narrow segments of the spectrum corresponding to molecular absorption bands.

Between two successive elementary scattering events on aerosols light quanta pass through a certain distance in the gaseous medium where their scattering and absorption by gas molecules occur. As shown by theory (see for example the work of H. van de Hulst and W. Irvine [45,46]), the optical length of the light path in the process of multiple scattering and molecular absorption in the cloud layer may be sufficiently great so that the reflectivity of the cloud layer in wavelengths corresponding to molecular absorption bands will be noticeably lower than in adjacent segments of the continuous spectrum.

As is known the radiation transfer equation in a dispersive, absorbent medium with a spherical indicatrix of scattering may be presented in the following form:

$$\cos\vartheta \frac{dI(\tau,\vartheta)}{d\tau} = -I(\tau,\vartheta) + \frac{\omega}{2}\int_0^{\pi} I(\tau,\vartheta')\sin\vartheta' d\vartheta' + \frac{\omega}{4\pi} I_0 e^{-\tau\sec\vartheta_0}, \qquad (1.10)$$

where ϑ_0 is the angle of incidence of direct solar radiation on the surface of the dispersive medium; ϑ is the exit angle of a ray scattered by the elementary volume of the medium; ϑ' is the angle of incidence of diffusely scattered

radiation on the volume of the medium under consideration; τ is the optical depth; I_0 is the intensity of incident solar radiation; I is the intensity of diffusely scattered radiation in a given direction; ω is part of the scattered radiation in the total quantity of radiation absorbed by the medium (where $\omega = 1$, the medium is purely scattered, and where $\omega = 0$ only pure absorption occurs accompanied by a transformation of radiant energy into other forms of energy). Methods of solving the transport equations were set forth in detail in works by V. A. Ambartsumyan [40,43], V. V. Sobolev [41] and S. Chandrasekar [42]. It is the final result which is now important to us. The intensity of radiation diffusely scattered in a given direction by a plane /22
layer of infinite optical thickness with a spherical scattering indicatrix equals

$$I(\eta, \xi) = \frac{\omega}{4} S \frac{\xi}{\xi+\eta} \varphi(\eta) \varphi(\xi). \tag{1.11}$$

Here $\xi = \cos i$, $\eta = \cos \varepsilon$ (i and ε are angles of incidence and reflection); S is incident radiation intensity; $\phi(\eta)$ and $\phi(\xi)$ are auxiliary functions introduced by Ambartsumyan. Their numerical values are tabulated in the works by Ambartsumyan and Chandrasekar. Chandrasekar calls these H-functions. The value ω equals

$$\omega_{co} = \frac{\sigma}{\sigma + \varkappa_{co}}. \tag{1.12}$$

where σ and κ_{co} are the scattering factor and true absorption coefficient, respectively, on cloud layer particles. The formula (1.12) is written for the continuous spectrum. In the absorption band

$$\omega_{ab} = \frac{\sigma}{\sigma + \varkappa_{co} + \varkappa_{ab} \frac{P_{eff}}{P_0}}, \tag{1.13}$$

where κ_{ab} is the molecular absorption coefficient; P_{eff}/P_0 is a factor which allows for the dependence of the absorption coefficient on pressure and its change with depth in the cloud layer. It is clear that where the wavelength is the same, $\omega_{ab} < \omega_{co}$. In utilizing formula (1.11), we may write the equation for residual intensity at any point in the absorption band which develops in the cloud layer for the case of equality $\eta = \xi$:

$$\frac{I_{ab}(\eta)}{I_{co}(\eta)} = \frac{\omega_{ab}}{\omega_{co}} \frac{\varphi^2_{ab}(\eta)}{\varphi^2_{co}(\eta)}. \tag{1.14}$$

Correspondingly the albedo for the cloud surface

$$A = 1 - \varphi(\eta) \sqrt{1 - \omega} \tag{1.15}$$

in the wavelengths which correspond to the absorption band will be reduced and even with the absence of absorption in the atmosphere above the clouds in the Jovian spectrum we would observe molecular bands. Of course for this it is required that the density of the dispersed phase of the cloud layer not be excessively high. We find from (1.12) and (1.13), omitting the pressure change correction, that

$$\frac{\varkappa_{ab}}{\sigma}=\frac{1}{\omega_{ab}}-\frac{1}{\omega_{co}}=\frac{\omega_{co}-\omega_{ab}}{\omega_{co}\omega_{ab}}. \qquad (1.16)$$

If this ratio is close to zero, i.e., if the scattering coefficient exceeds the molecular absorption coefficient by several orders of magnitude, then the difference between ω_{co} and ω_{ab} will be insignificant. Then we shall not detect the molecular absorption band in the spectrum. /23 We shall see what the ratio κ_{ab}/σ equals if $\omega_{co} - \omega_{ab} \geqslant 0.01$, i.e., when the absorption is sufficiently pronounced. The dependence of κ_{ab}/σ on ω_{co} where $\omega_{co} - \omega_{ab} = 0.01$ is shown in Figure 5. We see that for the red part of the spectrum, where the molecular absorption bands are mainly observed and where $\omega_{co} > 0.95$, the minimal ratio κ_{ab}/σ at which absorption in the cloud layer is detected, equals $\sim 10^{-2}$, i.e., $\sigma \approx 100\ \kappa_{ab}$. It is possible to show, for example, that in the CH_4 band (6190 Å) methane absorption in the cloud layer will cause the appearance of a pronounced absorption band if $\sigma \leqslant 0.8 \cdot 10^{-3}$ cm^{-1}. In terrestrial stratus-like clouds the scattering factor equals σ = (2 to 4)$\cdot 10^{-4}$ cm^{-1}, and here their very pronounced influence on the intensification of telluric oxygen and water vapor absorption lines is observed [150].

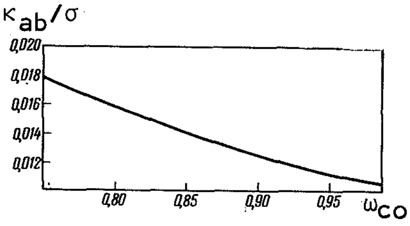

Figure 5. The Dependence of κ_{ab}/σ on ω_{co} Where $\omega_{co} - \omega_{ab}$ = 0.01.

Figure 6 shows that the intensity of the absorption band generated during multiple scattering in the cloud layer decreases toward the limbs of the planetary disk.

e) The cumulative effect of absorption in the cloud layer and in the outer atmosphere. Since in fact an outer atmosphere exists above the cloud layer of Jupiter, mainly consisting of absorbent gases in discrete segments of the spectrum, the molecular absorption distribution observed over the planetary disk must conform to a certain cumulative effect in which the relative role of the outer atmosphere in the cloud layer depends mainly on two parameters: the content of a given gas in the atmosphere and the scattering /24 factor of the cloud layer. If the optical thickness of the outer atmosphere in a given point of the absorption band equals τ_{ab} and if scattering in the outer atmosphere may be disregarded (τ_{ab} = 0) then an equation for residual intensity in a given wavelength may be written in the following form

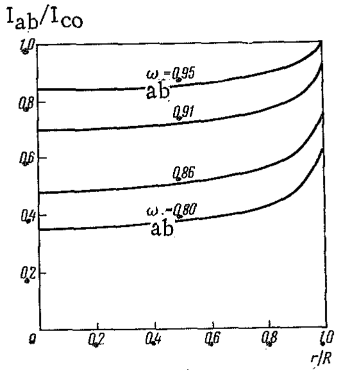

Figure 6. Molecular Absorption Behavior Over the Disk of a Planet Surrounded by a Cloud Layer with $\tau_{co} = \infty$ and $\omega_{co} = 0.97$ with No Atmosphere Above the Cloud Level.

$$\frac{I_{ab}(\eta)}{I_{co}(\eta)} = \frac{\omega_{ab}}{\omega_{co}} \left[\frac{\varphi_{ab}(\eta)}{\varphi_{co}(\eta)}\right] e^{\frac{-2\tau_{ab}}{\eta}}. \qquad (1.17)$$

Calculations in accordance with this formula (Figure 7) reveal that absorption behavior over the planetary disk in this case may be different. A decrease in absorption toward the limb, if τ_{ab} is very small and the practical constancy of absorption over the entire disk, with the exception of the limb itself which is usually inaccessible for exact measurements, and an increase of absorption toward the limb with a relatively large optical thickness of the outer atmosphere or during high scattering coefficient values in the cloud layer may all be observed. It is perfectly obvious that not knowing the distribution of absorption along the disk in a given band, it is not possible to give a decisive quantitative interpretation of absorption band intensity observed in the integral spectrum of the planet and it is not possible to compare the intensity of planetary absorption bands with laboratory bands without having first clarified the role of absorption in the cloud layer.

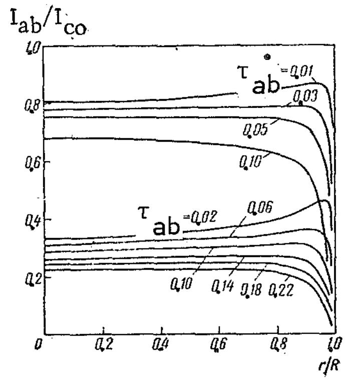

Figure 7. Molecular Absorption Behavior Over the Planetary Disk Surrounded by a Cloud Layer and the Presence of an Outer Atmosphere with an Optical Thickness of τ_{ab} in the Absorption Band. Upper curves--for $\omega_{co} = 0.97$, $\omega_{ab} = .95$; lower curves--for $\omega_{co} = 0.97$; $\omega_{ab} = 0.80$.

Measurements of methane absorption band intensity conducted by the author [33,36,37] form a basis for the conclusion that absorption in the outer atmosphere amounts to not more than 25% of the total /25
absorption observed in CH_4 bands in the visible and near-infrared regions of the spectrum. Correspondingly the methane content in the outer atmosphere must be several times less than the value determined by Kuiper of 15,000 cm-STP for a single-layer model. The same situation must also occur for ammonia and hydrogen. We have only Hess' measurements for NH_3, but these are very uncertain since due to the low intensity of the band 6443 Å, measurement errors prove to be of the order of differences in the equivalent width of the band for various zones of the Jovian disk. The intensity of hydrogen absorption lines on the Jovian disk, in accordance with data furnished by Spinrad and Trafton [23] do not change with the shift from the center toward the limbs of the disk. However we must keep in mind that for lines and bands of different intensity the

influence of absorption in the cloud layer leads to dissimilar effects. According to J. Chamberlain [48], the effective optical depth of the formation of the absorption line in the cloud layer equals

$$\tau_{\text{eff}} = \frac{1-(1-\omega)^{1/2}+(1-\omega)\eta\sqrt{3}\,(1-\eta\sqrt{3})}{\sqrt{3}\,(1-\omega)^{1/2}\,[1-\eta\sqrt{3}\,(1-\omega)^{1/2}]}. \qquad (1.18)$$

The less the absorption the deeper the light quanta penetrate into the cloud layer with multiple scattering. Therefore if both scattering and molecular absorption occur in the cloud layer the weak absorption lines and bands will lead to a determination on this basis of a larger gas content than the strong lines.

If the cloud layer does not absorb in the continuous spectrum, i.e., if the aerosols furnish pure scattering, without true absorption, then for the center of any line or molecular band with absorption coefficient κ_{ab} in the near-infrared region we may establish the following relationship between ω_{ab} and the optical thickness τ_{ab} of the outer atmosphere:

$$\omega_{ab} = \frac{1}{\omega_{co} + \varkappa_{ab}\dfrac{P_{\text{eff}}}{P_0}\sigma^{-1}} \simeq (1 + k\tau_{ab})^{-1}, \qquad (1.19)$$

where $k = 1/\sigma_0 H$; σ_0 is the scattering factor; H is the altitude of the single-layer atmosphere. Using the formulas mentioned above we may calculate the relationship between residual intensity values $B = (I_{ab}/I_{co})_{\eta = 1}$ in the center of a given absorption band and darkening toward the limb $\beta = I_{\eta = 0.5}/I_{\eta = 1.0}$ in the absorption band with consideration for absorption both in the cloud layer and in the outer atmosphere. This relationship for various k values is shown in Figure 8. Where $k \gg 1$ the main role in the formation of absorption bands is played by the cloud layer, and where $k \ll 1$ absorption mainly occurs in the outer atmosphere. Through the use of this graph and /26 through the measurement of absorption band intensity in the center of the disk and at points with $\cos\vartheta = 0.5$ it is possible to estimate the relative role of the outer atmosphere in the cloud layer in the formation of absorption lines and bands. According to absorption band intensity measurements in the near-infrared range (from 0.6 to 1.0 μ) the value of the k parameter for methane on Jupiter probably lies within the range from 0.5 to 2.0. This means that molecular absorption by methane in the cloud layer has a relatively pronounced effect on absorption band intensity observed and must be considered in interpreting absorption spectra and in determining the quantitative chemical composition of the Jovian atmosphere. The same applies, although to a different degree, to other gas components in the atmosphere of Jupiter detected by the spectroscopic method (ammonia and hydrogen). As yet there are no reliable photometric measurements for these gases in various segments of the Jovian disk. It is true that we may note that absorption in the cloud layer must play a more significant role for ammonia, the concentration of which increases more rapidly with depth than the concentration of uncondensed CH_4.

We should note that all calculations mentioned above are based on the assumption that the absorption coefficient and scattering factor in the cloud layer of Jupiter change proportionately with depth, i.e., that ω_{ab} (z) = const. In a real atmosphere this condition may not be fulfilled, since a change in the density of the dispersed phase (or the "water content" as it is called in meteorology) of the clouds may proceed with depth in accordance with a different law than a change in density of the gas absorbed; here the function ω_{ab} (z) would be different for condensing NH_3 and non-condensing CH_4. The derivation of analytical formulas for arbitrary laws of the change in ω_{ab} with depth is very complex. Therefore the method of statistical tests (the Monte-Carlo method) with the use of an electronic digital computer may prove to be more effective for appropriate calculations of molecular absorption intensity where ω_{ab} depends on depth. This method is already employed in calculation of the optical properties of earth clouds.

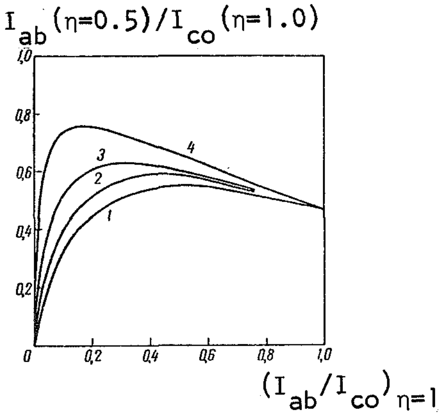

Figure 8. The Relationship Between Absorption Band Intensity and Darkening Toward the Limb of the Disk in the Center of the Absorption Band. Curves are calculated for cases: 1, k = 0.5; 2, k = 1.0; 3, k = = 2.0; 4, k = 10.

§3. Mean Molecular Weight of the Outer Atmosphere

a) Spectral observation data. Spectral observations give us incomplete information concerning the chemical composition of the planetary atmosphere, first of all because several gases do not absorb light in a spectral region accessible for observations. Therefore even the precise qualitative composition of the Jovian atmosphere is thus far unknown. Based on available spectral analysis data we may assume that the atmosphere of Jupiter consists of hydrogen, methane and ammonia. We shall assume that this is, in fact, true. Then the /27
mean molecular weight of the atmosphere

$$\bar{\mu} = \frac{\sum\limits_n \mu_n N_n}{\sum\limits_n N_n} \qquad (1.20)$$

(μ_n represent molecular weights, N_n is the number of molecules of each of the gas components) for Jupiter will equal 2.4-2.0 depending mainly on the quantity of molecular hydrogen assumed; if the hydrogen content is 27 km-atm then the relative quantities of methane and ammonia are insignificant.

Now if we could arrange to determine the value $\bar{\mu}$ by an independent method and without utilizing spectral measurements, we could establish how much complete information spectral observations have given us concerning the composition of the atmosphere.

b) Observation of star occultations. In order to determine independently the mean molecular weight of the atmosphere it is necessary to find an optical phenomenon in the planetary atmosphere which depends in some manner on μ. Such a phenomenon exists; it is refraction attenuation of star brightness during occultation of the star by the limb of the planetary disk. Unfortunately only one such important observation has thus far been made for Jupiter, on November 20, 1952. W. Baum and A. Code [49] observed photoelectrically the occultation by Jupiter of the star σ Arietis. The method of observations and the method with which they determine the value $\bar{\mu}$ are set forth in detail in the book by V. V. Sharonov [39], and therefore we shall discuss only the results here.

The theory of the refraction attenuation of the light of a star during light passage through the planetary atmosphere gives us, in the final analysis, an equation which links the change in brightness Φ of the star with time t in connection with two parameters b and v; v is the relative velocity of observer displacement in a plane perpendicular to the direction of the planet (the value is constant and is easily determined), and parameter b is a quantity which is the reciprocal of the altitude of the uniform atmosphere, i.e.,

$$b = \frac{1}{H} = \frac{g\bar{\mu}}{RT}. \qquad (1.21)$$

It is possible to calculate theoretically the curves of the drop in brightness of the star during occultation by the planet with various values of parameter b with the aid of the equation

$$\left(\frac{\Phi_0}{\Phi} - 2\right) + \ln\left(\frac{\Phi_0}{\Phi} - 1\right) = bvt \qquad (1.22)$$

and to compare with the results of the calculations a curve obtained from direct measurements of star brightness (Figure 9). Non-uniformity in the drop in brightness of σ Arietis is associated with fluctuations in the light flow caused by turbulence in the atmospheres of Jupiter and the earth. In the overall picture the observational curve agreed best of all with a theoretical curve calculated for the parameter b = 0.12. Knowing the value b, we can also find the mean molecular weight of the Jovian atmosphere (of the outermost layers, of course) /28

$$\bar{\mu} = \frac{bRT}{g}, \qquad (1.23)$$

for which it is only necessary to establish a specific value for the temperature of the outer atmosphere. The relationship between b, T and $\bar{\mu}$ is illustrated in Table 1.7.

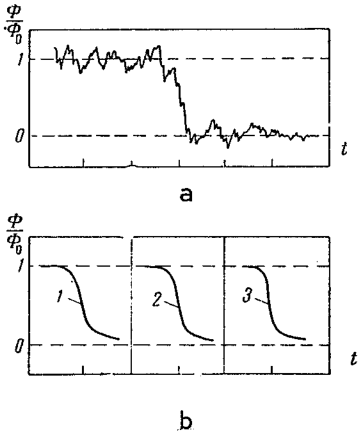

Figure 9. Observational (a) and Theoretical (b) Curves of the Drop in Stellar Brightness During Occultation by Jupiter (According to Baum and Code). 1, b = 0.08; 2, b = 0.12; 3, b = 0.16 [see 1.22].

TABLE 1.7. MEAN MOLECULAR ATMOSPHERIC WEIGHT WITH DIFFERENT b AND T VALUES

T, °K	μ		
	b = 0,08 км⁻¹	b = 0,12 км⁻¹	b = 0,16 км⁻¹
70	1,8	2,7	3,6
86	2,2	3,3	4,4
100	2,6	3,8	5,1

In order to establish temperature, Baum and Code used an estimate by G. Kuiper [3] of the temperature of the isothermal stratosphere of Jupiter of 86°K, from which the mean molecular weight proved to equal $\bar{\mu}$ = 3.3. Subsequently E. Öpik [50], in examining the condition of radiant equilibrium in the Jovian stratosphere and accepting as a base not the radiation temperature, as Kuiper did, but the radiometric temperature of Jupiter (130°K), obtained the value T = 112 ± 2°K. From this /29
value we have, correspondingly, $\bar{\mu}$ = 4.3. One way or another, but according to the observations of the occultation of σ Arietis, the mean molecular weight of the outer Jovian atmosphere proves to be 1.5-2 times greater than calculated under the assumption that the Jovian atmosphere consists only of hydrogen, methane and ammonia. A pronounced quantity of a gas heavier than hydrogen must be present in the atmosphere of Jupiter.

§4. The Relative Content of Gaseous Components

a) The most probable components of the Jovian atmosphere. In order to explain the value obtained for the mean molecular weight of the outer atmosphere which exceeds the molecular weight of a mixture of hydrogen, methane and ammonia alone, we must assume that a certain gas is present in the atmosphere which is heavier than hydrogen. Such a gas might be helium (μ = 4) and several other mainly inert gases which do not enter into chemical reactions. Table 1.8, which is based on Kuiper's data [3], contains several basic physical constants of those gases, the presence of which in the Jovian atmosphere is either established or which may be assumed with "greatest" justification.

Apparently all of the free nitrogen and oxygen entered into a combination with hydrogen which formed ammonia and water. The latter must be completely /30
frozen in the upper layers of the atmosphere and may be present in all three phases only at great depths.

TABLE 1.8. GASES POSSIBLY PRESENT IN THE JOVIAN ATMOSPHERE

Gas	Formula	Molecular weight,	Boiling point, K	Melting point, K	Approximate density g/cm^3	
			At a pressure of 760 mm Hg		Liquid phase	Solid phase
Hydrogen	H_2	2.0	20	14	0.08	0.08
Helium	He	4.0	4	—	0.15	—
Nitrogen	N_2	28.0	77	63	0.87	1.03
Oxygen	O_2	32.0	90	55	1.30	1.43
Neon	Ne	20.2	27	24	1.20	—
Argon	Ar	39.9	87	84	1.40	1.65
Water	H_2O	18.0	373	273	1.00	0.92
Ammonia	NH_3	17.0	240	195	0.66	0.82
Methane	CH_4	16.0	112	89	0.42	—

Note: The isotope composition of the elements is assumed to be the same as on the Earth.

There may also be present in the atmosphere of Jupiter various more complex chemical compounds not having excessively high molecular weights and boiling points, i.e., compounds which may be present in pronounced quantities in the gaseous state at temperatures 100-170°K.

We may attempt to detect such substances by means of spectroscopic observations. In addition, several compounds may be in a liquid or solid state in the atmosphere if the dimensions of the drops or crystals are sufficiently small to provide for an extended period for these compounds in the dispersed phase in the upper layers of the Jovian atmosphere. Table 1.9 shows the most probable of these.

TABLE 1.9. SEVERAL CHEMICAL COMPOUNDS WHICH MAY POSSIBLY BE PRESENT IN THE JOVIAN ATMOSPHERE

Compound	Formula	μ	Melting point °K	Boiling point °K
			At a pressure of 760 mm Hg	
Hydrogen fluoride	HF	20.0	190	292
Hydrogen chloride	HCl	36.5	162	188
Hydrogen sulfide	H_2S	34.1	190	213
Phosphine	PH_3	34.0	141	186
Acetylene	C_2H_2	26.0	—	189
Ethylene	C_2H_4	28.0	104	169
Ethane	C_2H_6	30.0	101	185
Silane	SiH_4	32.1	88	61
Carbon dioxide	CO_2	44.0	—	195
Hydrocyanic acid	HCN	27.0	259	289

Careful searches in the atmosphere of Jupiter for a number of the chemical compounds shown in Table 1.9 by means of comparing laboratory spectra of these compounds with Jovian spectra, photographed with sufficiently high dispersion, were undertaken by T. Owen [53,55]. However with the exception of methane and ammonia, Owen was not able to find in the Jovian spectra a single absorption band for other hydrocarbon and hydronitric compounds, or for silane and deuterium hydride (HD). Previously J. Bardwell and G. Herzberg [54] also attempted to find in the spectrum of Jupiter and of other giant planets silane and methyl deuteride (CH_3D) absorption; substances for which laboratory spectra had already been investigated. A search for indications of /31 absorption of other substances, undertaken by H. Spinrad and L. Trafton [23], ended with the same results. It is true that the investigators found two unidentified lines at λ 6292.72 and 6368.46 Å in the Jovian spectrum. Thus far there is no observational data available which confirms the presence in the atmosphere of Jupiter of the compounds indicated above. But this does not mean that such substances are not present in the atmosphere; it is simply that their content may prove to be less than the amount required for the substances to be detected spectroscopically. In this respect the laboratory experiments of C. Sagan and S. Miller [57,139] are interesting. They simulated the Jovian atmosphere under laboratory conditions with a mixture of hydrogen, methane and ammonia in a ratio of 30:3:1 respectively, and passed electrical discharges through the mixture. A subsequent analysis of the mixture by means of infrared and mass spectroscopy detected the presence of molecules of ethane, acetylene, ethylene, hydrocyanic acid and several other compounds. These experiments refuted the opinion that more complex molecules could not form from methane and ammonia in the presence of an excess of hydrogen. One result of the experiment which must be acknowledged as very important is the fact that the mixture resulted in the formation of acetylene which under Jovian atmospheric conditions must polymerize intensively, while creating different high-temperature molecular compounds, many of which have bright coloring.

According to a proposal by H. Urey and A. Brewer [58,59], a number of chemical compounds (free radicals) and ions may appear in the upper layers of the Jovian atmosphere under the influence of solar ultraviolet radiation. These are NH_2, N_2^+, CN, CH_2, CH^+, CH and C_2. R. Wildt [60] and F. Rice [61] believe that free radicals may also play a significant role in the formation of bright coloration of Jovian cloud details.

b) Models of the chemical composition of the atmosphere. In 1952 Kuiper [3] proposed two models of the relative chemical composition of the Jovian atmosphere based on data from spectral determinations of the quantity of methane and ammonia and on several considerations pertaining to the composition of the gaseous envelope of a protoplanet. The first model (a) (Table 1.10) leads to a mean molecular atmospheric weight $\overline{\mu} = 2.48$. In the b model the relative content of H_2 and He was established on the basis of spectral data from the atmospheres of Uranus and Neptune; absorption bands of molecular hydrogen had already been detected in the spectra of these planets. In this connection the mean molecular weight of the atmosphere obtained equaled

$\bar{\mu} = 3.26$. This value coincides very well with the results of observations of occultation of σ Arietis. The basic role in the atmosphere of Jupiter is played by molecular hydrogen and by the lightest of the inert gases--helium, which, as assumed, also causes the high $\bar{\mu}$ value.

TABLE 1.10. THE RELATIVE CHEMICAL COMPOSITION OF THE JOVIAN ATMOSPHERE (NUMBER OF MOLECULES IN %)

Author	H_2	He	Ne	Ar	CH_4	NH_3
G. Kuiper [3], model a	78,4	21,7	0,074	0,010	0,018	
G. Kuiper [3], model b	38,5	61,2			0,28	
E. Öpik [50]	2,3	97,2	0,39	0,042	0,063	0,003
H. Spinrad and L. Trafton [23]	60	36	3		<1	<1
G. Field [52]	72,9	22,7	2,0	Traces	2,0	0,3
W. Tanaka [205]	38,9	60,8	0,19	—	0,15	—
J. Beckman [206]	69,7	29,9	0,2	—	0,1	—
V. I. Moroz [208]	73	26	—	—	0,05	—
B. Sodek [210]	44,83	53,95	0,22	0,01	0,26	0,08

Tr. Note: Commas indicate decimal points.

E. Öpik [50], on the basis of a mean molecular weight $\bar{\mu} = 4.3 \pm 0.5$ and an optical thickness of the outer atmosphere $\tau = 0.25$ at λ 3900 Å, which he established, came to the conclusion of the predominance of helium in the Jovian atmosphere. According to his model $\mu = 4.02$. This version coincides in the best way with the value $\bar{\mu}$ cited above of the five possible models examined by Öpik. However this model differs sharply with data concerning the cosmic abundance of elements; according to a recent summary by L. Aller [51] the ratio H/He = 6.2, i.e., hydrogen atoms in space are on the average approximately six times more plentiful than helium atoms. Although Öpik also made an attempt to explain the helium surplus by hydrogen precipitation in the form of "snowflakes" on the surface of the primary planet, his model does not agree with observations since it results in an excessively high pressure on the surface of the cloud layer. /32

According to recent spectrographic observations H. Spinrad and L. Trafton [23] fixed the ratio of concentrations $H_2/(He + Ne + Ar) \geqslant 0.55$, on the basis of which they proposed a model of the chemical composition with a preponderance of hydrogen. A similar model was proposed by G. Field, based on cosmic element content, as a working model for various calculations. Thus a majority of investigators agreed on the fact that hydrogen and helium are present in the Jovian atmosphere in comparatively similar quantities, although there is still no uniform opinion concerning which of these gases is predominant. It seems to us that considerations of a cosmogonic nature (which are themselves hypothetical) should not be employed as arguments in favor of one or another hypothesis of the chemical composition of the atmosphere. On the contrary, observational data must be employed as a check on the line of reasoning of hypotheses advanced for the origin of the planets.

c) The overall chemical composition of the planet. The low mean density of Jupiter indicates that it cannot consist on the whole of heavy substances with a molecular weight essentially greater than four. However heavy substances may be concentrated somewhere near the center of the planet, forming a very dense core, surrounded by a thick envelope of low-density substances. The degree of planetary non-uniformity is characterized by the dimensionless value J/MR^2, where M is the planetary mass, R is the radius, and J is the maximum moment of inertia of a spherical body with respect to the rotational axis: /33

$$J = \frac{8\pi}{3}\int_0^R \rho r^4 dr \tag{1.24}$$

($\rho = \rho(r)$ is density at point r). For a uniform globe $J/MR^2 = 0.4$, which is the maximum value. The J/MR^2 value for the planets is determined approximately by the flattening observed. For the earth $J/MR^2 = 0.334$, and for Jupiter and Saturn J/MR^2 approaches 0.2. It is difficult to determine this value exactly for the giant planets since with low values for J/MR^2 the formula which links J/MR^2 with flattening becomes inexact. But in any case it is clear that Jupiter is characterized by significantly greater non-uniformity in matter distribution than the earth.

The equilibrium state of the planet may be characterized by three equations, including the hydrostatic equilibrium equation

$$\frac{dP}{dr} = -\frac{GM_r}{r^2}\rho, \tag{1.25}$$

the equation for mass, assuming a spherical symmetrical density distribution,

$$\frac{dM_r}{dr} = 4\pi r^2 \rho \tag{1.26}$$

and the equation of state for planetary matter

$$P = P(\rho, \bar{\mu}, T). \tag{1.27}$$

If we know the equation of state then for a planet with known M and R with a given chemical composition we may find the pressure and density distribution with depth by means of (1.25) and (1.26). It is necessary to select the chemical composition of the planet (of the external layers and of the core) in such a manner that the density distribution satisfies the value of moment of inertia J/MR^2, found from observations. It is apparent from this how closely associated are the problems of the chemical composition and the internal structure of the planet. Only a joint solution of both problems is possible. /34

Here we shall not discuss in detail problems of the internal structure of Jupiter but shall refer the reader to the works of V. G. Fesenkov and A. G. Masevich [63], A. A. Abrikosov [64] to the extensive survey of R. Wildt [62] and to the recent article of P. Peebles [65]. The main conclusion which touches upon the chemical composition of Jupiter and which the above-named authors and other investigators have expressed (N. A. Kozyrev [66], H. Brown [67], W. De Marcus [69], S. V. Kozlovskaya [68], etc.) consists of the fact that the predominant component of Jupiter is hydrogen. This is well illustrated by the graph (Figure 10), borrowed from the work of A. G. Masevich [71], which shows the mass-radius relationship curves for a body consisting of matter which is in a degenerated state. Matter in the depths of the planet must also be in the same state, since the pressure reaches hundreds of thousands and even hundreds of millions of atmospheres. The curves in Figure 10 are calculated for hydrogen, methane, ammonia, oxygen and iron in accordance with the calculations of H. Sen [70] and the graph also shows points which correspond to the dimensions and masses of planets of the solar system. Jupiter and Saturn fall between curves for hydrogen and methane which means that they may not consist wholly of substances which are significantly heavier than hydrogen, whereas, on the other hand, they may not wholly consist of pure hydrogen. If we were to attempt to construct a model of Jupiter based on methane alone, then the mean density of the planet would significantly exceed the value observed. Purely hydrogen models, which have been calculated by many authors, lead to an excessively high moment of inertia. It is necessary to assume the presence of heavier substances in the depths of Jupiter in order to satisfy observational data. Among those which may be predominant is helium which follows hydrogen in cosmic abundance and which due to separation by diffusion may be concentrated in the central parts of Jupiter. Insofar as quantitative considerations are concerned the majority of authors agree that Jupiter consists of approximately 80% by mass of hydrogen. Not more than 20% of the mass of this planet is shared by other elements and chemical compounds.

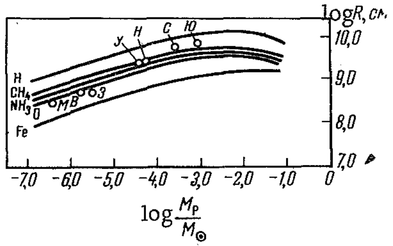

*Figure 10. Theoretical Mass-Radius Relationship for Bodies Consisting of Matter in a Degenerated State (According to A. G. Masevich).

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*Translator's Note: In the figure the symbols (letters) stand for individual planets:

м = Mars; в = Venus; э = Earth; у = Uranus; с = Saturn; ю = Jupiter; and н = Neptune.

CHAPTER 2.

PLANETARY TEMPERATURE CONDITIONS

§1. The Cycle of the Irradiation of Jupiter by Solar Radiation

a) The solar constant. The temperature conditions of planets which have no /35 intrinsic heat sources are determined mainly by the quantity of radiation (radiant energy) which arrives from the sun. On Jupiter at least the upper layers of the atmosphere depend exclusively on the flow of solar energy which is absorbed by gas molecules and cloud particles. However judging by available data an important role in overall Jovian atmospheric conditions may also be played by internal planetary heat.

The mean distance of Jupiter from the sun is 777.8 million km or 5.203 AU. If the solar constant for the earth (the quantity of radiant energy which falls per unit time per unit time area, perpendicular to the solar rays and at the limits of the atmosphere) equals ~1.98 cal/cm^2 min, then for Jupiter this value must be 27 times less, i.e., approximately 0.07 cal/cm^2 min. The eccentricity of the Jovian orbit (0.048) is of sufficient magnitude so that the radius vector of the planet changes within the limits 4.953 to 5.453 AU. Correspondingly the radiation flux received by the Jovian surfaces changes by approximately 20% in the course of a half-period of the rotation of Jupiter around the sun.

b) The illumination of Jupiter by solar rays. The angle of incident of solar rays (i) for any point on the Jovian disk, and therefore, the illumination of the surface may be calculated in accordance with the following formulas:

$$\cos i' = \sin \varphi \sin \delta_{\odot} + \cos \varphi \cos \delta_{\odot} \cos \lambda, \tag{2.1}$$

$$\tan \Delta\varphi = \frac{e_{\text{♃}}^2 \tan\varphi}{1 - e_{\text{♃}}^2 + \tan^2 \varphi}, \tag{2.2}$$

$$\cos i = \cos \Delta\varphi \cos i' + \frac{\sin \Delta\varphi}{\cos \varphi} (\sin \delta_{\odot} - \sin \varphi \cos i'), \tag{2.3}$$

where ϕ is the zenographic latitude of the planetary point; λ is its zenographic longitude from the meridian passing through the sub-solar point; $\delta_{\odot}$ is the zenocentric inclination of the sun ($-3^\circ \leqslant \delta_{\odot} \leqslant +3^\circ$); i' is the angle of /36 incident measured from the vector radius of the planetary point; $\Delta\phi$ is the difference between the zenographic and astronomical latitude, which is linked with the ellipticity of Jupiter; $e_{\text{♃}}$ is the eccentricity of the ellipsoid of the planet. Where $\delta_{\odot} = 0$ the formulas are simplified, since if we accept $e_{\text{♃}}^2 = 0.123$, we have

$$\cos i = \cos i' (\cos \Delta\varphi - \sin \Delta\varphi \tan \varphi) = \cos (\varphi + \Delta\varphi) \cos \lambda, \tag{2.4}$$

$$\tan\Delta\varphi = \frac{0{,}123\tan\varphi}{0{,}877+\tan^2\varphi}. \tag{2.5}$$

In accordance with these formulas it is not difficult to calculate the position of lines of equal illumination on the Jovian disk (Figure 11).

The quantity of energy which impinges upon a unit area of the cloud surface of Jupiter with solar zenith distance $z_{\odot} = i$ during time dt, equals

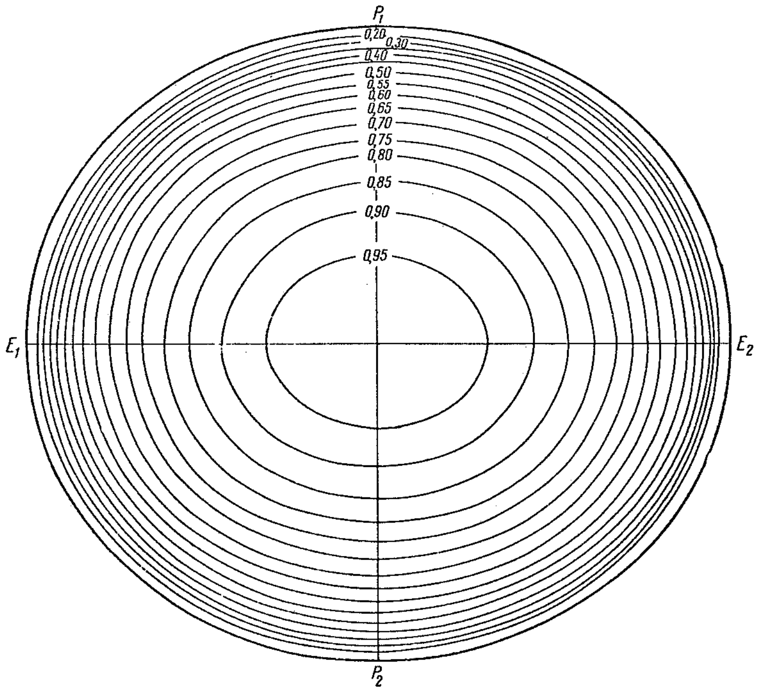


Figure 11. Lines of Equal Intensity on the Jovian Disk at Phase Angle α = 0.

$$dE = E_0 \cos z_{\odot} k^{\sec z_{\odot}} dt, \tag{2.6}$$

where E_0 is the quantity of radiant energy which falls per unit time on a unit area normal to the solar rays beyond the limits of the Jovian atmosphere, i.e., the solar constant; k is the mean transmission coefficient for the Jovian atmosphere for the entire spectral range. If P is the rotation period for a given Jovian latitude zone, then /37

$$dt = \frac{P}{2\pi} d\lambda \tag{2.7}$$

and where $\delta_{\odot} = 0$ the total quantity of energy obtained by a single segment of the cloud surface of Jupiter in the course of an entire Jovian day equals

$$E = E_0 \frac{P}{2\pi} \int\limits_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} \cos(\varphi + \Delta\varphi) \cos \lambda k^{\frac{\lambda}{\cos(\varphi+\Delta\varphi)\cos\lambda}} d\lambda. \tag{2.8}$$

Due to the small inclination of the equator of Jupiter to the orbital plane, illumination conditions for practically all zones of Jupiter, with the exception of near-polar areas, remain practically fixed during the course of the year. In the near-polar areas the change of $z_{\odot}$ by 6° exerts a pronounced effect on the total quantity of energy delivered.

§2. The Theoretical Temperature of Jupiter

a) The temperature of an absolutely black body. In the place of Jupiter let us imagine a spherical planet which possesses the properties of an absolutely black body. Its temperature will be determined by the quantity of energy accepted and returned; the body will be warmed while absorbing radiation up to the point where equilibrium is established between absorption and the intrinsic radiation of the body. The temperature thus established is called the equilibrium temperature and is found from the energy balance equation. If the body is absolutely black and is heated identically at all points it will absorb and radiate the same quantity of energy

$$E_{\text{ab}} = \frac{\pi R^2 S_0}{r^2}, \tag{2.9}$$

where S_0 is the solar constant for the earth; r is the radius vector of the planet in AU; R is the planetary radius. But the quantity of energy radiated by a body with temperature T in accordance with the Stefan-Boltzmann law

$$E_{\text{ab}} = \sigma T^4 \cdot 4\pi R^2. \tag{2.10}$$

Thus the temperature of an absolutely black body, which absorbs solar radiation is /38

$$T_a = \sqrt[4]{\frac{S_0}{4\sigma r^2}} = \frac{279\text{°K}}{\sqrt{r}}. \tag{2.11}$$

For a body located at distance r = 5.2 AU, T_a = 122°K. If only the surface of the body is heated, and heat does not penetrate inside, the temperature of each surface segment will be determined only by absorption and emission of radiation by this segment so that for a unit area, normal to the solar rays,

$$T_b = \sqrt[4]{\frac{S_0}{\sigma r^2}} = \frac{395}{\sqrt{r}} = T_a \sqrt{2}. \qquad (2.12)$$

In our case T_b = 173°K. This is the maximum temperature which would be acquired by the absolutely black surface of a non-heat conducting planet at the sub-solar point. In other sections of the planet the temperature would change in proportion to $\sqrt[4]{\cos i}$. It is completely obvious that the properties of a real planet differ from the properties of an absolutely black body. However the calculation shown does indicate that the temperature of Jupiter on its visible surface cannot be above -100°C.

b) The radiation temperature of Jupiter. Since the albedo of Jupiter (A) does not equal zero the planetary surface reflects part of the radiation which falls upon it. Correspondingly the planetary temperature must be less than T_b. According to Kuiper [3], the maximum radiation temperature of the planetary surface equals

$$T_m = T_b \sqrt[4]{1 - A} = \frac{395 \sqrt[4]{1 - A}}{\sqrt{r}}, \qquad (2.13)$$

and the mean planetary temperature is

$$T_A = \frac{T_m}{\sqrt{2}}. \qquad (2.14)$$

The best approximation in temperature calculations is obtained through the use of the visual albedo of the planet which corresponds approximately to that region of the spectrum which contains the centroid of the distribution curve for the energy spectrum of solar radiation. The Jovian surface in the visible region of the spectrum absorbs 1 - A = 0.49 of the incident radiation. Therefore for Jupiter $T_m = 0.838\ T_b$ = 145°K and T_A = 102°K. The latter value is usually quoted in literature as the radiation temperature of Jupiter. But many factors have not been taken into consideration in its calculation, such as the rapid rotation of Jupiter which must decrease the value of the ratio T_m/T_A, condensation and evaporation processes in the planetary cloud layer, /39 transparency of the outer atmosphere, the behavior of the albedo along the spectrum, the change in radiation capability in accordance with the spectrum, etc.

On the basis of the results of photoelectric spectrophotrometry of Jupiter in λλ 3400-10000 Å, in 1965 D. Taylor [75] calculated the bolometric albedo of Jupiter which characterizes the reflectivity and absorptivity of the planet in the entire range:

$$A_{♃} = \frac{r^2 d^2}{R^2 S_0} \int\limits_0^\infty F_{\lambda ♃} q_\lambda d\lambda, \qquad (2.15)$$

where S_0 is the solar constant; r and d represent the distance of Jupiter from the sun and the earth; R is the mean radius of the planet; $F_{\lambda ♃}$ is the radiation flux from Jupiter; q_λ is a phase integral taken as 1.6. The bolometric spherical albedo obtained in this case equals $A_{♃} = 0.45$ with an accuracy up to 15%. Thus the radiation temperature of Jupiter must equal 105 ± 3°K.

c) The temperature of the cloud surface. If we consider that the cloud cover of Jupiter consists mainly of products of ammonia condensation or sublimation, we may estimate the Jovian cloud layer surface temperatûre, in the vicinity of which we must observe equilibrium between the processes of the formation of NH_3 crystals or drops and their evaporation. Ammonia must be in a state of saturation in this region. A unique dependence [50] exists between the pressure of saturated ammonia vapors and temperature:

$$\log P_V = -\frac{1550}{T} + 4\log T + 4{,}58 - 8 \cdot 10^{-5} T^{1,8}. \qquad (2.16)$$

If the partial ammonia pressure is known at the upper cloud limit, then the temperature is determined simply in accordance with Table 2.1. Kuiper [3], in accepting the NH_3 content in the outer atmosphere as equal to 700 cm-STP, obtained a cloud surface temperature for model b equal to T_0 = 168°K. In fact, the mass of ammonia in an outer atmosphere column with a 1 cm² base equals $m_a = 0.53$ g/cm² and NH_3 partial pressure $P_a = m_a g = 1{,}380$ dyne/cm². Considering that $P_V = P_a$, we obtain the value T_0 indicated above.

Utilizing the data of Baum and Code concerning the altitude of the uniform atmosphere of Jupiter and assuming H ≃ 10 km for ammonia in the outer atmosphere, Öpik finds the different cloud temperature value T_0 = 156°K and P_a = 400 dyne/cm².

Since the ammonia content according to Kuiper was introduced on the basis of a single-layer model of an absorbent atmosphere, then as already noted in /40
preceding chapter, it must be decreased by several times if molecular absorption partially occurs in the cloud layer. Therefore only the probable limits of 150 to 170°K may be established for the temperature of the surface of the Jovian cloud layer. But even with this degree of uncertainty it is clear that this temperature is higher than the theoretically calculated radiation temperature of Jupiter.

$$\frac{T_{da}}{T_{br}}=\sqrt[4]{\frac{1-A_{da}}{1-A_{br}}}, \qquad (2.17)$$

where T_{da} and T_{br}, A_{da} and A_{dr} are radiation temperatures and visual albedos /41
of the dark and bright Jovian zones, respectively.

TABLE 2.1. NH_3 SATURATED VAPOR PRESSURES AND NUMBER OF MOLECULES PER UNIT VOLUME AS A FUNCTION OF TEMPERATURE

T,°K	log P_V	P_V,dyne,cm^2	log N	N, molecules/cm^3
50	—19,71	$1,95\times10^{-20}$	—5,55	$2,82\times10^{-6}$
60	14,24	$5,75\times10^{-15}$	—0,16	$6,92\times10^{-1}$
70	10,41	$3,90\times10^{-11}$	+3,61	$4,07\times10^{3}$
80	7,41	$3,90\times10^{-8}$	6,45	$2,82\times10^{6}$
90	5,05	$8,90\times10^{-6}$	8,86	$7,25\times10^{8}$
100	3,24	$5,75\times10^{-4}$	10,62	$4,16\times10^{10}$
110	1,72	$1,90\times10^{-2}$	12,10	$1,26\times10^{12}$
120	—0,45	$3,55\times10^{-1}$	13,33	$2,14\times10^{13}$
130	+0,63	3,64	14,38	$2,40\times10^{14}$
140	1,49	47,7	15,20	$1,58\times10^{15}$
150	2,33	$1,72\times10^{2}$	16,01	$1,02\times10^{16}$
160	2,98	$9,56\times10^{2}$	16,64	$4,36\times10^{16}$
170	3,54	$3,47\times10^{3}$	17,17	$1,48\times10^{17}$
180	4,07	$1,18\times10^{4}$	17,68	$4,79\times10^{17}$
190	4,52	$3,31\times10^{4}$	18,11	$1,29\times10^{18}$
200	4,92	$8,32\times10^{4}$	18,48	$3,02\times10^{18}$
210	5,28	$1,90\times10^{5}$	18,82	$6,60\times10^{18}$
220	5,58	$3,80\times10^{5}$	19,10	$1,26\times10^{19}$

Tr. Note: Commas indicate decimal points.

d) Anticipated differences in the temperature of bright and dark belts. Dark regions on the Jovian disk which absorb solar radiation more intensively correspondingly must also have a higher temperature in comparison with bright zones. Without consideration for details associated with a possible difference in the chemical and phase composition of matter in the dark and bright formations, it is possible to find the upper limits of the temperature differences by using formula (2.13) for the maximum radiation temperature:

The maximum difference in the albedo between the dark bands and the bright zones on Jupiter during the last 50 years was observed in 1962, when the entire equatorial region of Jupiter was occupied by a broad dark band. At that time even in red and green rays the relative brightness of the band amounted to 0.85 and 0.73, respectively, of the brightness of the bright zones, and in blue and violet rays, these values were 0.60 and 0.50. If we accept the albedo of the "bright" substance in green rays as equal to 0.65, then the albedo the dark band substance will be 0.48 and the ratio T_{da}/T_{br} will equal 1.11. Therefore the maximum temperature difference will not exceed 12-18°K.

The actual difference in temperature will be lower, since in (2.17) it was accepted that the radiating power of the clouds in the infrared region equals unity, and this, strictly speaking, is not true. If the albedo of the cloud layer in the infrared region (A') for the dark zones is lower than for the bright zones then in place of (2.17) we have

$$\frac{T_{da}}{T_{br}}=\sqrt[4]{\frac{1-A_{da}}{1-A_{br}}\frac{1-A'_{br}}{1-A'_{da}}}. \tag{2.18}$$

The first factor under the radical is more than one and the second is less than one, so that the entire expression under the radical differs only slightly from unity. Of course these calculations are extremely simplified but a more detailed analysis would have no meaning since the exact physical chemical composition of the Jovian clouds is thus far unknown.

§3. Radiometric Temperature

a) The spectral region of measurement. For the present the greater part of radiometric measurements are accomplished from the surface of the earth and therefore the range of infrared radiation wavelengths which impinges upon radiation receivers is very small due to intensive absorption of radiation in the earths atmosphere. Powerful absorption bands of water vapor, oxygen and other gases (Figure 12) noticeable attenuate radiation arriving from celestial bodies in the region 0.7 to 5.5 μ, completely extinguish radiation in wave lengths 5.5 to 8 μ and beginning with 14 μ up to the microwave radio band (wavelengths of several mm), so that it is only that in the segment from 8 to 14 μ and partially in the range 2-5.5 μ that thermal radiation of celestial objects may be measured from the earth. The second transparent "window" presents interest only for investigations of high-temperature sources (T > 400°K), which have a sufficient amount of intrinsic thermal radiation in this area.

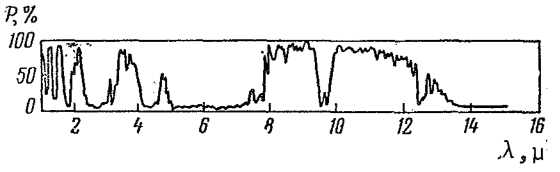


Figure 12. Light Transmission in the Earth's Atmosphere in the Range 1-15 μ.

For weakly heated bodies with a temperature of 130-150°K the maximum of thermal radiation occurs, as can be seen from Figure 13, in the region of approximately 20 μ; here practically all the radiation of such bodies lies in wavelengths greater than 8 μ. In this situation in contrast to what occurs for bodies with a temperature of several hundred degrees the earth's atmosphere transmits less than 10% of the total radiation. The thermal radiation flux from a black body with $T_1 = 130°K$ is less than the radiation flux from a body of $T_2 = 400°K$ by $(T_2/T_1)^4 = 90$ times. Radiation from a body with $T = 130°K$, received through the earth's atmosphere, will be reduced by approximately 360 times if we consider the opacity of the earth's atmosphere for $\lambda\lambda > 14$ μ. This means that the sensitivity of thermal radiation receivers for radiometric observations of Jupiter must be several hundred times greater than those acceptable during observations of the moon, for example. /42

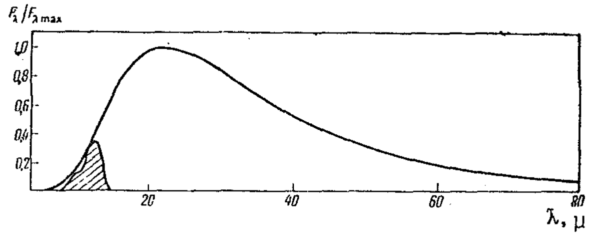


Figure 13. Spectral Radiation Density Distribution of a Black Body With T = 130°K. The dashed area is the "transparent window" of the earth's atmosphere.

The change in thermal radiation flux relative magnitude in the region λλ 8-14 μ with temperature may be seen from Table 2.2 which was taken from the work [76]. The Table shows flux values normalized for the radiation of a body with T = 237°K, the flux of which is accepted as equal to 1.

b) The integral temperature of Jupiter. If we consider the planet to be a uniform sphere which radiates in an absolutely black body then its temperature may be determined after having measured the energy-producing illumination E of the planet (the quantity of energy radiated by the planet per unit area of the radiation receiver). Then the integral temperature is determined in accordance with the formula /43

$$T = \sqrt[4]{\frac{r^2E}{R^2\sigma}}, \qquad (2.19)$$

where r is the distance from the planet; R is the planetary radius; σ is the Stefan-Boltzmann constant. The energy-producing illumination is found from the radiometric (bolometric) magnitude (m_r) of the source of radiation [77]:

$$E = 17{,}3 \cdot 10^{-12} \cdot 2{,}512^{-m_r} \quad (\text{cal/cm}^2\ \text{min}).$$

We shall not state here all of the formulas employed for the introduction of radiometric measurement corrections for optics and thermal screen transmission, for the transparency of the earths atmosphere at various zenith distances and for radiation receiver characteristics. We shall point out certain results only.

In 1924 W. Coblentz and C. Lampland [78] conducted radiometric measurements of Jupiter at Lowell Observatory through the use of a thermocouple with a water shield which "cut off" thermal radiation and thereby permitted separating reflected solar and intrinsic planetary radiation. The reduction of the results of these measurements, accomplished during two nights only, was undertaken by D. Menzel, who had proposed his own theory for the processing of observations of this type. Temperature values of 140 and 120°K were found for the integral radiation of the entire Jovian disk.

TABLE 2.2. THE RELATIONSHIP BETWEEN BRIGHTNESS TEMPERATURE AND THERMAL RADIATION FLUX IN λλ 8-14 μ

T, °K	F_T/F_{273}	T, °K	F_T/F_{273}	T, °K	F_T/F_{273}	T, °K	F_T/F_{273}
100	2.79×10^{-4}	130	4.88×10^{-3}	155	2.39×10^{-2}	185	9.45×10^{-2}
105	4.99×10^{-4}	135	7.01×10^{-3}	160	3.11×10^{-2}	190	1.14×10^{-1}
110	8.50×10^{-4}	140	9.83×10^{-3}	165	3.98×10^{-2}	195	1.37×10^{-1}
115	1.39×10^{-3}	145	1.35×10^{-2}	170	5.03×10^{-2}	200	1.62×10^{-1}
120	2.18×10^{-3}	150	1.81×10^{-2}	175	6.28×10^{-2}		
125	3.31×10^{-3}			180	7.74×10^{-2}		

According to measurements by E. Pettit and S. Nicholson [79], the bolometric value of Jupiter, calculated for 1 square second of arc of the planetary disk in accordance with integral radiation proved to equal $4^{m}.94$ (the average of 15 measurements which resulted in values from $4^{m}.83$ to $5^{m}.14$). Intrinsic planetary radiation amounted to only about 8% of the total radiation received; therefore the total bolometric magnitude of Jupiter for thermal radiation equals $7^{m}.68$, from which the integral temperature equals ~150°K.

W. Sinton and J. Strong [97] at the Mount Wilson Observatory in 1952 de- /44
termined the Jovian temperature as 130-133°K.

c) Temperature distribution on the Jovian disk. The comparatively low sensitivity of thermal receivers employed by the investigators named above permitted them to measure only radiation from the entire Jovian disk. It was only recently, in 1962, that measurements of the brightness temperature distribution on the Jovian disk were accomplished for the first time; for this purpose B. Murray, R. Wildey and J. Westphal [76] utilized a highly-sensitive photometer with a quantum infrared detector, mounted on the 5 m telescope of the Mount Palomar Observatory. The input aperture of the photometer had a diameter equal to 1/8 of the diameter of the Jovian image. The image of the planet was displaced with respect to the aperture along the diurnal parallel and a record of the radiation intensity was made on a recorder. Isotherm charts were compiled from 7-8 photometric profiles of the disk. Within the limits of measurement accuracy these isotherms have a symmetrical and almost circular shape which corresponds to a small drop in temperature toward the limbs of the disk. The average temperature at the center of the disk was 128.4°K.

In December 1963 temperature measurements on the Jovian disk were again accomplished by the same researchers, but with a radiation receiver of twice the resolution of that used previously; the receiver diaphragm isolated approximately 1/17 of the equatorial diameter of the planet [80]. A map of brightness temperature isophotes, averaged for several night observations,
is shown in Figure 14. The temperature at the center of the Jovian disk is /45
129°K. The isophote pattern is approximately symmetrical with respect to the equator while the difference in temperatures between the dark and bright planetary belts are very small--not more than 0°.5. Two bright zones at lower

latitudes appear to be colder than the dark equatorial band. The isophotes pass symmetrically within this band with respect to the central meridian of Jupiter; however in the northern temperate zone this symmetry is disrupted--on the morning side the bright zone appears to be relatively darker than on the evening side. Differences in brightness temperature isophote pattern are also observed between the north and south polar regions. As yet, however, these results are not very reliable since during subsequent scannings of the disk several positional errors and noises appeared which led to an apparent shift of isophotes and to the appearance of maps of false structural details.

Toward the limbs of the Jovian disk the temperature drops a total of 3-4°K at a distance from the center of 0.8 of the disk radius. Unfortunately measurements of the limb itself cannot be accomplished due to difficulties in establishing the exact position of the limb on graphic registers. Therefore there is still no data on the existence of specific brightness temperature asymmetry which reflects a difference in the thermal cycle of the morning and evening terminator of the planet.

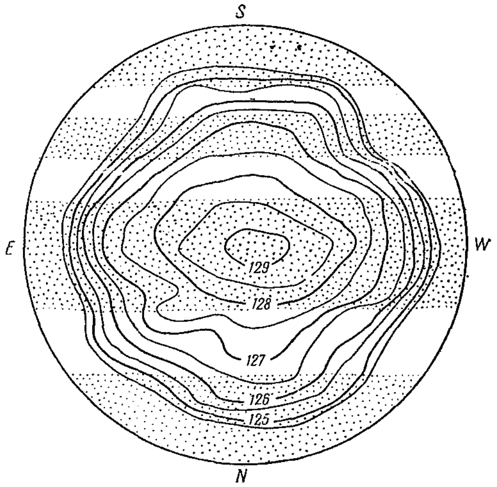


Figure 14. Averaged Isophotes on the Jovian Disk (After Murray, Wildey and Westphal). The numbers on the curves are brightness temperatures.

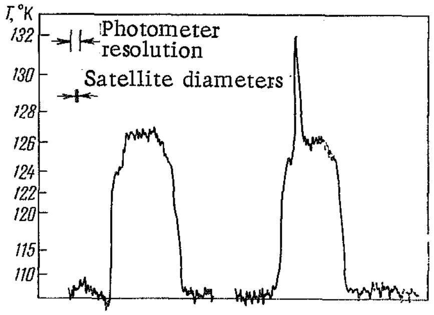


Figure 15. Photoelectric Recordings of Temperature Distribution on the Jovian Disk in λλ 8-14 μ With a Radiation Burst Corresponding to the Shadow of Satellite III on the Disk (After Murray, Wildey and Westphal).

d) Temperature anomalies in the satellite shadow zone. During scanning of the Jovian disk the same researchers [76] detected a completely unexpected phenomenon; when a region of Jupiter with a satellite shadow fell upon the photometer input aperture the graphic register displayed a sharp burst corresponding to a significantly higher temperature (Figure 15). Such an effect was noted in the shadow of the J II and J III satellites (Table 2.3). Correction /46 of the values obtained for shadow and input diaphragm dimensions and also processing of the results under the assumption that all of the additional radiation is generated only in the main body of the shadow or in both the main body and in the penumbra, as can be seen from the Table, lead to the fact that satellite shadow brightness temperatures of 190°K or 160°K are obtained. Even the latter value exceeds by more than 30° the temperature of Jovian regions illuminated by the sun.

On December 14, 1964 and February 4, 1965 R. Wildey [81] again measured the temperature in the shadow zones of the Io and Europa satellites utilizing high resolution, but detected no increase in temperature in the shadows. On this basis Wildey believes that the effect of the anamolous temperature increase has a temporary nature, since he does not doubt the reality of results obtained in 1962.

The phenomenon discovered by Murray, Wildey and Westphal presents a tremendous amount of interest, provided it was not caused by some kind of instrumental effects.

TABLE 2.3. THE JOVIAN TEMPERATURE IN SATELLITE SHADOW ZONES

Satellite	Date, 1962, Universal time	Ratio of shadow solid angles and photometer field of view		Ratio of measured results (shadow + Jupiter and Jupiter)	Mean brightness temperature of the shadow (°K)	
		shadow main body	full shadow		shadow main body	full shadow
III	Oct.26.1^h30^m	$3,09 \cdot 10^{-2}$	$1,33 \cdot 10^{-1}$	1,657	184,5	155,5
II	Dec.15.1^h30^m	$6,93 \cdot 10^{-3}$	$2,53 \cdot 10^{-2}$	1,18	190	160
	1^h35^m			1,23	196	164,5
	1^h40^m			1,19	191	161

Tr. Note--commas indicate decimal points.

e) The radio temperature of Jupiter. Brightness temperature measurements of Jupiter according to its radio-frequency radiation were accomplished in recent years at many radio astronomical observatories in a wide range of wave lengths. A rather complete survey of such measurements is contained in [82], and therefore here we shall discuss only certain results which pertain to the optically observed zone of the Jovian atmosphere. The brightness radio temperature of Jupiter, as we see from Figure 16, begins with approximately with $\lambda = 5$ cm and sharply increases with wavelengths. If at $\lambda \simeq 3$ cm, the brightness temperature $T_B \simeq 200$°K, then at wavelength of approximately 1 m, T_B attains a value of 100,000°K! It is completely obvious that at $\lambda\lambda > 3$ we are dealing with radio frequency radiation of non-thermal origin which is created, apparently, in atmospheric layers which are located much higher than the cloud cover surface; these are in the ionosphere and in radiation belts which are situated at distances 2-3 Jovian radii from the cloud surface. The radio temperature in $\lambda\lambda \leqslant 3$ cm must correspond to the thermal radiation of Jupiter. /47
Estimates of the temperature in the 3 cm band, shown in Table 2.4, leads to a

rather sharp discrepancy in values--from 140 to 200°K. Apparently the nonthermal component in this band still makes a certain contribution to overall radio frequency radiation, perhaps even of a transient nature. In 1962, D. Thornton and W. Welch [88] measured the brightness radio temperature of Jupiter on the 8.35 mm wavelength by means of a 3-m radio telescope with a modulated radiometer. Here the temperature must agree only with thermal radiation. It proved to equal $T_B = 144 \pm 23$°K.

Thus radio observations nevertheless result in a Jovian temperature of at least 15°K higher than the value established by infrared Jovian radiation in λλ 8-14 μ.

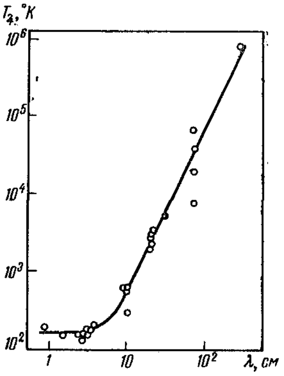


Figure 16. The Radio Frequency Radiation Spectrum of Jupiter (After V. V. Zheleznyakov).

TABLE 2.4. THE RADIO FREQUENCY BRIGHTNESS TEMPERATURE OF JUPITER ACCORDING TO MEASUREMENTS IN THE 3-CM BAND

λ, см	T_B, °K	Source	λ, см	T_B, °K	Source
3,02	185±30	[83]	3,17	173±20	[84]
3,03	171±20	[84]	3,3	193±16	[86]
3,15	140±38	[85]	3,36	189±20	[84]
3,15	145±18	[85]	3,75	200	[87]

Tr. Note - Commas indicate decimal points.

f) Spectroscopic temperature evaluations. Temperature evaluations of the atmosphere which are independent of planetary thermal radiation measurements may be accomplished according to the intensity of rotational lines in molecular absorption bands of the planetary spectrum. As is known [11,12], the number of molecules which are in a state of rotational energy which corresponds to the level with rotational quantum number J, is determined by the /48
formula

$$N_J \sim g_J e^{-\frac{F(J)\,hc}{kT}}, \tag{2.20}$$

where g_J is the statistical weight of the level; k is the Boltzmann constant; T is absolute temperature;

$$F(J) \simeq BJ(J+1). \tag{2.21}$$

The rotational constant is

$$B = \frac{h}{8\pi^2 c I_B} = \frac{27{,}994 \cdot 10^{-40}\, cм^{-1}}{I_B}, \tag{2.22}$$

where $I_B = \mu r^2 = \Sigma m_i r_i^2$ is the moment of inertia of the molecule ($\mu = m_1 m_2 / /m_1 + m_2$) is the reduced mass of a diatomic molecule.

Knowing the ratio of the populations of two rotational levels which is determined in accordance with the equivalent widths of the rotational lines

$$W_i \sim \alpha_c f_i N_i, \tag{2.23}$$

where $\alpha_c = \pi e^2/mc = 0.0265\ cm^2/sec$ and f_i is oscillator strength, it is possible by utilizing formula (2.20) to determine the temperature of that layer of the atmosphere in which basic absorption in specified lines is developed.

Based on the spectrograms of Keiss and Corliss, F. Zabriskie [22] measured the equivalent widths of two lines of molecular hydrogen in the band 8270 Å: S (1) - W_1 = 0.08 ± 0.01 Å and S (0) - W_0 = 0.04 ± 0.01 Å. Knowing the ratio of the corresponding oscillator strength $f_1/f_0 = 0.63$, Zabriskie used the method described above to obtain the rotational temperature $T_{ro} \simeq 170°K$. Here he assumes the lines were not saturated. Based on the fact that line S (2) was noticeable although weak, Zabriskie came to the conclusion that in any case the temperature cannot be less than 170°K but might even be greater, even 200°K.

Judging by the same H_2 lines H. Spinrad [89] defined the rotational temperature $T_{ro} \simeq 120°K$, since the equivalent line widths were evaluated by him at 0.04 and 0.03 Å [23]. These lines were very fine and weak and therefore the photometry associated with them was very difficult and temperature estimates, of course, cannot be considered reliable.

In 1965 T. Owen [55] measured the intensity of four rotational lines in the methane absorption band at λ 11057 Å ($3\nu_3$) from two spectrograms of Jupiter which Kuiper had obtained in 1955 (dispersion 71 Å/mm). Similar measurements were made with CH_4 laboratory spectra obtained at temperatures ~ 295 and ~ 210°K were calculated. The theoretical intensities of these lines for T = 200 and 175°K were calculated. The best, although incomplete, agreement among observations, laboratory measurements and theory was obtained for /49 relative intensity where T ≃ 200°K (Figure 17). Due to the fact that the spectrograms were not photometrically calibrated and due to a degree of uncertainty in line intensity evaluations, Owen believes the resultant error to be relatively great, so that T_{ro} = 200 ± 25°K.

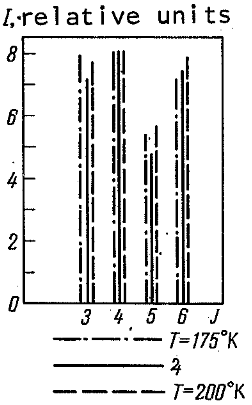


Figure 17. A Comparison of Theoretical Line Intensities in the CH_4 Band at 11057 Å Where T = 175 and 200°K With Observations in the Spectrum of Jupiter (After Owen).

In 1967 M. Walker and S. Hayes [211], with the aid of an electron-optical converter, obtained spectrograms of the CH_4 band at 11057 Å and measured the intensity of rotational line in the band, which they then compared with the theoretically calculated dependence of intensity on temperature. The result was extremely indefinite; the various lines furnished T_{ro} values from 100 to 300°K.

T. Owen (in a private communication) assumes that the reason for this lies in nonuniformity in the utilization of rotational constants, introduced for the fundamental frequency ν_3, in calculations for the harmonic bands. A comparison with laboratory spectra of the CH_4 $3\nu_3$ band leads to a value T_{ro} ≃ 180 ± ± 20°K.

As we have seen, spectroscopic temperatures also prove to be essentially higher than those obtained from infrared radiometric measurements. This may be partially explained by the fact that spectroscopic determinations of T_{ro} pertain rather to a certain level within the cloud layer whereas the radiometric temperature characterizes a certain level of the atmosphere above the clouds.

Spectral determinations of temperature apparently represent, at the present time, the single possibility of studying temperature gradients between individual zones and details on the surface of the Jovian cloud layer, as well as temporary temperature changes. It is true that in this respect practically nothing has been accomplished thus far. Only Spinrad and Trafton [23] have /50 devoted attention to variability in the intensity of individual lines in the NH_3 band at 6440 Å, having studied two spectrograms of Jupiter obtained in 1957 and 1961. There are indications available of significant changes in the intensity of this band with time [3] but the changes were not detected during a specially conducted investigation at the Astrophysical Institute of the Academy of Sciences of the Kazakh SSR.

§4. The Interpretation of Temperature Changes

a) Infrared molecular absorption in the atmosphere of Jupiter. It is known that ammonia strongly absorbs infrared radiation, while intensive NH_3 absorption bands lie in the region of the radiometric transparent "window" of the earths atmosphere (Figure 18). A certain amount of absorption was also caused by methane. Table 2.5 shows a list of the basic absorption intervals of methane and ammonia in agreement with a summary of Öpik [50] with an indication of the effective width of each interval ($\Delta\lambda$) and the average cross-section of absorption per molecule within the limits of this width.

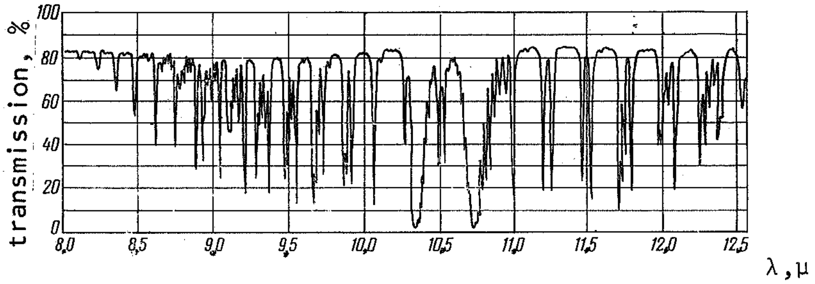


Figure 18. Ammonia Absorption Spectrum. Thickness of the Layer is 10 cm-atm (After A. Kross [185]).

The wavelengths in the Table do not correspond to the centers of the absorption bands but only indicate the position of the effective absorption interval. The effective absorption section characterizes, together with the number of molecules per cm^3, the absorption coefficient

$$\kappa = \sigma_{ab} N \qquad (2.24)$$

and the optical thickness of the absorbent layer

$$\tau_{ab} = \sigma_{ab} \int N dx = \sigma \sum N, \qquad (2.25)$$

where ΣN is the number of molecules in a vertical gas column with base area 1 cm^2.

TABLE 2.5. NH_3 AND CH_4 EFFECTIVE ABSORPTION INTERVALS IN THE INFRARED SPECTRUM

Molecule	λ, μ	Δλ, μ	σ_{ab}, cm^2	Molecule	λ, μ	Δλ, μ	σ_{ab}, cm^2
NH_3	1,6	0,4	$4,5\cdot10^{-23}$	NH_3	11,55	0,28	$1,3\cdot10^{-19}$
CH_4	7,7	1,0	$4,1\cdot10^{-21}$	NH_3	12,65	0,88	$6,7\cdot10^{-20}$
NH_3	9,75	0,66	$5,3\cdot10^{-20}$	NH_3	18,4	2,0	$3,2\cdot10^{-21}$
NH_3	10,65	0,38	$1,3\cdot10^{-19}$				

Tr. Note:-commas indicate decimal points.

In the region of the radiometric window λλ 8-14 μ separate wavelengths intervals are included as strong absorption intervals as well as intervals with relatively weak absorption. The former correspond to strong absorption bands which are detectable in laboratory spectra and for which the values σ_{ab} may be determined; the latter correspond to the weak bands, not observed in laboratory spectra, for which it is possible to indicate only the upper limits σ_{ab}. "Transparent" and "non-transparent" components consist of mutually overlapping bands. In Table 2.6, also compiled by Öpik [50], these bands are not separated and only the resultant effect is given for each component in a given wave length interval. /51

TABLE 2.6. CH_4 AND NH_3 ABSORPTION IN THE TRANSPARENT ATMOSPHERIC WINDOW 8-14 μ

Molecules	Limits, λ, μ	Strong absorption		Weak absorption	
		Δλ, μ	σ_{ab}, cm^2	Δλ, μ	σ_{ab}, cm^2
CH_4	8,0—9,2	0,20	$4\cdot10^{-21}$	1,00	$<10^{-23}$
NH_3	9,2—10,3	0,66	$5,3\cdot10^{-20}$	0,44	$<3\cdot10^{-21}$
NH_3	10,3—11,0	0,35	$1,3\cdot10^{-19}$	0,35	$1,3\cdot10^{-20}$
NH_3	11,0—12,1	0,28	$1,3\cdot10^{-19}$	0,82	$<3\cdot10^{-21}$
NH_3	12,1—13,2	0,88	$6,7\cdot10^{-20}$	0,22	$<3\cdot10^{-21}$
NH_3	13,2—14,0	—	—	0,80	$\leqslant10^{-22}$

Tr. Note:--commas indicate decimal points.

Even if the quantity of ammonia in the layer above the clouds were decreased by three times, and with consideration for partial absorption in the cloud layer, the optical thickness of the outer atmosphere in the region of the infrared NH_3 absorption bands would equal $\tau_{ab} = \sigma_{ab} n_0 L = 10^{-19}\cdot2.69\cdot10^{19}\cdot$ $\cdot230 = 620$ (we took L = 230 cm-atm in place of 700 cm-atm, after Kuiper). This means that the outer atmosphere of Jupiter is completely opaque for the thermal radiation of the surface of the planetary cloud layer. A layer of 1 cm-atm of ammonia has an optical thickness when $\sigma_{ab} = 10^{-19}$ cm^2, $\tau_{ab1} \simeq 2.7$, i.e., such a layer transmits less than 7% of the incident radiation. In intervals of "transparent" components, where $\sigma_{ab} < 3\cdot10^{21}$ cm^2, $\tau_{ab1} < 0.08$. Since the "transparent" absorption components occupy relatively only about 55% of the 8-14 μ region, on the average the optical thickness of a 1 cm-atm ammonia layer in this region amounts to approximately 1. /52

A similar picture is also observed in the millimeter radio wave band which is also intensively absorbed by ammonia. According to the calculations of A. P. Naumov and I. T. Khizhnyakov [92], the optical thickness of the outer atmosphere is $\tau \geqslant 1$ in the range from 1 to 1.5 cm. In the narrow interval of approximately 1.2 cm $\tau > 100$. But in $\lambda\lambda < 0.9$ and $\lambda\lambda > 1.7$ cm, $\tau < 1$, so that thermal radio frequency radiation of the cloud layer may radiate outward practically without attenuation. Therefore measurements of the brightness temperature of Jupiter on the 8.35 mm and 3 cm waves must correspond to the temperature at the level of the cloud surface or even layers at greater depths.

b) The position of the effective radiation level. If the law of the change in the density of the Jovian atmosphere with altitude is known to us and if we assume that the ammonia above the cloud layer is in a state approaching saturation, then we may attempt to evaluate the altitude of a layer the radiation of which corresponds to the Jovian radiometric temperature observed.

The temperature obtained from the relationship $P_V(T) = 120°K$ [see (2.16)] at a level above which 1 cm-atm of ammonia is located under ammonia saturation conditions. In fact at this level the temperature must be higher since in the layer above the clouds $T > T_{sat}$ (the ammonia is not condensed). Therefore as an approximation we may consider that the radiometric temperature 128-130°K also corresponds to this level. According to Kuiper this level is located at an altitude of approximately 10 km above the cloud surface.

Öpik [50], who considers that the effective optical depth of the radiating layer is $\tau = 2/3$ determines the corresponding number of NH_3 molecules above 1 cm^2 of the surface of the radiating layer and finds the ammonia vapor pressures above this layer

$$P(NH_3) = \frac{1{,}4\cdot10^{-20}}{\sigma_{ab}} \text{ (dyne/cm}^2\text{)}. \qquad (2.26)$$

If we substitute in this formula the values σ_{ab} from Table 2.6 and use 2.1 we may determine the lower limit (since Table 2.1 was compiled for saturated ammonia vapors) of the temperature of a layer the radiation of which at a given wave length may pass beyond the limits of the Jovian atmosphere. For "opaque" componenets of the absorption bands Öpik obtains on the average $T \geqslant 119°K$ and for "transparent" components, $T \geqslant 135°K$ with the exception of the edge of the transparent "window" itself, where $T \geqslant 148°K$. But the transmission of the earths atmosphere falls at the edge of the transparent "window" and therefore earth-based receivers almost fail to register this radiation. In any case it is apparent that even in the region of "transparent" segments of the radiometric "window", the thermal radiation of the surface of the cloud layer cannot be measured but radiation is received from only a certain layer of the outer atmosphere, the altitude of which insofar as radiation is concerned proves to be different at different wavelengths. /53

c) Temperature distribution on the Jovian disk. The reduction in brightness temperature observed along the limbs of the Jovian disk apparently does not reflect real temperature behavior on the planet but is a consequence of the specific nature of radiation transfer in a planetary atmosphere which exits at various angles. The transfer equation may be written in the form

$$\cos\vartheta \frac{dI(\tau,\vartheta)}{d\tau} = I(\tau,\vartheta) - \frac{1}{2}\int I(\tau,\vartheta)\sin\vartheta\, d\vartheta, \tag{2.27}$$

where τ is the optical thickness of the radiating volume element; ϑ is the angle of departure of radiation with respect to the normal. The solution for departing radiation may be presented for the limit of atmosphere ($\tau = 0$) in approximate form just as was done for a photosphere [90]:

$$I(0,\vartheta) = \int_0^\infty \frac{1}{2}\frac{S}{\pi}\left(1+\frac{3}{2}\tau\right)e^{-\tau\sec\vartheta}\sec\vartheta\, d\tau, \tag{2.28}$$

where S is the total radiation flux. This solution for a planetary atmosphere is not a strict one since the required condition of local thermodynamic equilibrium in planetary atmospheres is fulfilled only in comparatively dense layers [91]. Nevertheless it may be employed for preliminary interpretation of the brightness temperature distribution observed on the Jovian disk.

The mean optical depth at which the radiation develops and which departs at angle ϑ equals

$$\bar{\tau} = \frac{\int_0^\infty \tau\frac{1}{2}\frac{S}{\pi}\left(1+\frac{3}{2}\tau\right)e^{-\tau\sec\vartheta}\sec\vartheta\, d\tau}{\int_0^\infty \frac{1}{2}\frac{S}{\pi}\left(1+\frac{3}{2}\tau\right)e^{-\tau\sec\vartheta}\sec\vartheta\, d\tau} = \frac{\cos\vartheta\,(1+3\cos\vartheta)}{1+\frac{3}{2}\cos\vartheta}. \tag{2.29}$$

The values $\bar{\tau}$ for various radiation departure angles are given in the second column of Table 2.7 which also include calculated lower temperature limits of the effective radiation layer and corresponding values of the partial pressure of ammonia for the "transparent" and "non-transparent" absorption components in the 8-14 μ range. This Table shows that radiation of extreme areas which go beyond the limit of the Jovian atmosphere develop at a significantly smaller optical depth than radiation of the center of the disk.

TABLE 2.7. THE OPTICAL DEPTH, LOWER TEMPERATURE LIMITS AND NH_3 PARTIAL PRESSURE VALUES OF AN EFFECTIVE RADIATION LAYER CORRESPONDING TO RADIATION WITH AN ANGLE OF DEPARTURE ϑ (FOR L_{NH_3} = 700 cm-atm) /54

ϑ,°	$\bar{\tau}$	$\sigma_{ab} = 10^{-19}$ см^2		$\sigma_{ab} = 3 \cdot 10^{-21}$ см^2	
		P, dyne/cm^2	T, °K	P, dyne/cm^2	T, °K
0	1,60	0,333	110	11,2	135
10	1,57	0,330	120	11,0	134
20	1,49	0,312	119	10,4	134
30	1,36	0,286	119	9,55	134
40	1,17	0,246	119	8,20	133
50	0,96	0,202	118	6,72	132
60	0,71	0,149	117	4,96	130
70	0,46	0,096	116	3,22	129
75	0,33	0,070	114	2,31	127
80	0,21	0,044	113	1,47	125
85	0,10	0,021	110	0,70	122

Tr. Note: Commas indicate decimal points.

Figure 19 shows the temperature curve along the radius of the Jovian disk based on calculations cited (the upper and lower curves) and the mean temperature curve according to observational data of Murray, Wildey and Westphal. The observational curve lies between calculated curves and its behavior in general may be considered to agree well with calculated behavior, especially if we keep in the mind the uncertainty of initial values.

Measuring thermal radiation intensity of the cloud layer of Jupiter even /55 with the aid of infrared radiation receivers transported beyond the limits of the earth's atmosphere is not possible in a sufficiently wide in interval of wavelengths due to strong absorption by ammonia. Figure 20 shows what part of the thermal radiation of the planetary cloud cover with a temperature of 150°K is absorbed by NH_3 and what part by CH_4 in the range λλ 5-60 μ. Only in the range λλ 35-70 μ are intervals of the spectrum almost free from NH_3 absorption. In the future when the possibility of measuring Jovian thermal radiation from space probes develops the temperature of the cloud layer may be determined more reliably than the radiometric Jovian temperature already obtained, since near λλ 40-55 μ the level of radiation energy which corresponds to the relative behavior of the Planckian curve is several times greater than at λλ 8-14 μ. On the other hand, knowing that at specific wavelengths ammonia is not absorbent, and having determined at these wavelengths the temperature of the surface of the cloud layer (T_0), we might find the value of the ammonia content in the outer atmosphere from the difference between the observational spectral curve in the 15-35 μ region and the calculated Planckian curve for T_0. Here it is true that a difficulty arises which is associated with the fact that in the infrared region of the spectrum, judging by recent work [95, 180], rather strong absorption by molecular hydrogen occurs.

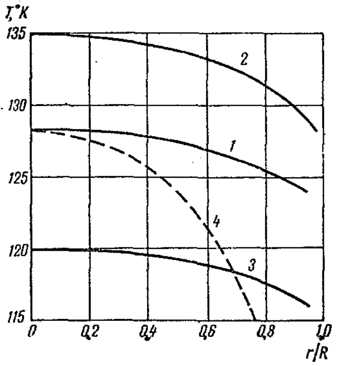


Figure 19. Observational (1) and Theoretical (2,3,4) Temperature Behavior on the Jovian Disk Plotted Under the Assumption That $\sigma_{ab} = 3 \cdot 10^{-21}$ cm^2 (2), $\sigma_{ab} = 10^{-19} \cdot cm^2$ (3) and $T = T_0 \sqrt{\cos\theta}$ (4) (see Table 2.7).

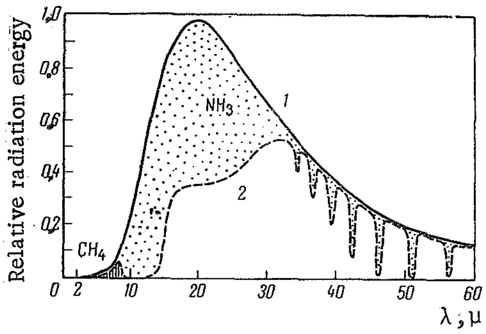


Figure 20. Thermal Radiation of the Cloud Layer of Jupiter Where T = 150°K (Curve 1) and After Absorption of Radiation by Methane and Ammonia (Curve 2) After Gross and Rasool [96].

Nevertheless spectral and radiometric measurements of Jovian radiation in narrow segments of the infrared spectrum have a great deal of significance since they make it possible to investigate radiation which arrives from various levels of the outer atmosphere. For this of course very sensitive radiation receivers are required, especially if the matter concerns observations from the earth. The possibility of "probing" the atmosphere of Jupiter also exists in /56
the radio range from 1.0 to 1.6 cm. But it is necessary to install a radio telescope at a great altitude or to transport it beyond the limits of the earths atmosphere in order to eliminate the influence of absorption by water vapor in this range.

d) Possible reasons for temperature anomalies in the satellite shadow zone. In the opinion of the authors who discovered this phenomenon there are two possible explanations for the increase in temperature observed on the Jovian disk in the locations where the satellite shadows fall. One explanation consists of the fact that with the cessation of irradiation by solar radiation of a certain part of the Jovian atmosphere, the equilibrium (phase or photochemical) changes in the atmosphere. This leads to a reduction in the concentration of those agents which cause atmospheric non-transparence for radiation at λλ 8-14 μ. Then the thermal radiation of deeper and hotter layers may escape outward.

The other explanation assumes that a change in the equilibrium state which begins with the cessation of insolation, causes an increase within the atmosphere of those very substances which develop a significant mean atmospheric opacity. Then the temperature gradient, usually close to the adiabatic, increases sharply, i.e., the temperature falls more quickly with altitude, which involves a convective atmospheric instability and carries the hotter masses of matter into atmospheric layers located at a greater altitude.

A simple calculation reveals that with the first version of the explanation of temperature anomalies not less than 0.18 g/cm^2 of ammonia must condense in the cloud region of the atmosphere. After approximately 30-50 min have passed this atmospheric area passes out of the shadow and the ammonia which previously condensed must again be transformed into the gaseous phase. It is possible to calculate that for this to occcur under the influence of solar radiation would require not less than 45 hours. In 30 min only approximately 0.0024 g/cm^2 of ammonia crystal may evaporate. The process of diffusion also occurs extremely slowly. If horizontal turbulent heat transfer were to play a significant role here it would have to develop an obstacle to the rapid condensation of ammonia in the shadow zone.

R. Wildey [93] accomplished several calculations associated with a possible increase in atmospheric radiation in the shadow zone while assuming the propagation in depth of a "transparent front." However for agreement between calculation and observation an excessively high thermal radiation increase with depth is required and excessively high values are demanded for the latent heat released by each gram of atmospheric matter. Therefore the problem of the temperature increase in the satellite shadow zone for the present remains unclear. Further observations of this phenomenon are required which must first of all confirm its reality and establish specific regularities in its appearance and disappearance under various Jovian atmospheric conditions.

§5. The Problem of the Sources of Thermal Energy on Jupiter /57

a) An excess of Jovian thermal radiation. The radiation temperature of Jupiter as a black radiater equals 105 ± 3°K. At the same time, according to independent observational data obtained during different years and with various instruments, the radiometric temperature of Jupiter on the average amounts to 130 ± 5°K. In either case we shall consider that the planetary radiating power η in the thermal range equals unity. If $\eta < 1$ then both the theoretical and observational value T will increase in proportion to $1/\sqrt[4]{\eta}$, since the temperature ratio remains the same. We cannot exclude of course that for one reason or another the difference in radiation and radiometric temperatures may be somewhat less, but it is hardly possible to reduce it to zero.

Apparently the rapid rotation of Jupiter is the basic reason for the fact that the difference in temperature between the limb and the center of the disk is much less than would be expected for a slowly rotating planet. Therefore if we accept the value 130°K, after Öpik [50], as the average planetary temperature, then the thermal radiation released from the Jovian surface appears to exceed the flow of solar heat by $(130/105)^4 \simeq 2.36$ times, i.e., Jupiter must possess inherent radiation which by $k \simeq 1.36$ times exceeds the radiation caused by heating of the planetary surface by solar radiation.

It is possible to conclude from this that in order to maintain the temperature observed a supplementary heat supply must be provided from the depths of the planet (or from the depths of atmospheric layers?). The value of this flux is

$$F_{♃} = kS\frac{\pi R^2}{4\pi R^2}(1-A) = k\frac{S_0}{4}(1-A), \tag{2.30}$$

where R is the radius of Jupiter; S_0 is the solar constant for Jupiter; A is the albedo of the planetary surface. If A = 0.45 [75], k = 1.36 and $S_0 = 0.075\ \text{cal/cm}^2\ \text{min} = 5.2 \cdot 10^4\ \text{erg/cm}^2\text{sec}$, then $F_{♃} = 9.8 \cdot 10^3\ \text{erg/cm}^2\text{sec}$. Insofar as the value of the estimate indicated is concerned, of course, it may fluctuate when the limits ±25%, considering the degree of uncertainty in basic values.

b) Internal heat sources. As early as 1951 N. A. Kozyrev [66] examined the opposite problem, having applied to Jupiter a mass-luminosity relationship developed in a theory of internal star structure and in theories already mentioned above involving the chemical composition and internal structure of this planet. He found that the pressure at the center of Jupiter must be $P_c = 5.6 \cdot 10^7$ atm, that density at the center $\rho_c \simeq 6.2\ \text{g/cm}^3$ and that the temperature must be $10^5 - 2 \cdot 10^5$°K, depending on what mean molecular weight (1 or 2) is accepted for the entire planet. The mass-luminosity relationship has the /58
following form:

$$F = \frac{\mu^4}{\varkappa}\frac{M^3}{R}, \tag{2.31}$$

where F is radiation flux; μ is molecular weight; M and R represent the mass radius of the body; κ is the absorption coefficient during thermal energy transfer by radiation. Considering that on Jupiter heat transfer from the depths of the planet occurs mainly due to thermal conductivity, Kozyrev introduced in place of κ a different absorption coefficient which corresponds to the difference between the thermal conductivity equation and the radiant transfer equation:

$$\varkappa^* = \frac{2{,}6T^{1/2}Z}{\rho}, \tag{2.32}$$

where ρ is density; T is temperature; Z is the index number of the element which is the basic planetary component. Where $T \simeq 10^5 - 2 \cdot 10^5$°K, Z = 1 (hydrogen) and $\rho \simeq 6$, we obtain $\kappa^{*} \simeq 100$. Then with μ equal to 1 or 2, the coefficient in the mass-luminosity ratio will be $\mu^4/\kappa^{*} \simeq 0.01\text{-}0.16$; here the average value of this quantity coincides with the coefficient μ^4/κ for the stars. Of course this coincidence is accidental. We may now determine the flux ratio for energy which emanates from Jupiter and from the sun:

$$\frac{F_{♃}}{F_{\odot}} = \left(\frac{M_{♃}}{M_{\odot}}\right)^{3} \left(\frac{R\odot}{R_{♃}}\right) . \qquad (2.33)$$

From this the inherent thermal radiation flow from Jupiter equals $F_{♃} = 6 \cdot 10^{3}$ erg/cm^{2}sec. This value shows very little difference from the value obtained in the preceding section. However the concurrence of these results does not support the validity of the initial proposals. According to Taylor [75], who based his opinion on the data of De Marcus, thermal conductivity cannot be the basic method of energy transfer from the depth of Jupiter. "Heat extraction" may occur due to convention in the Jovian mantle if the mantle substance is in a molten state, insufficiently transparent to radiation. If we assume that the source of internal heat is the heating up of central parts of the planet as a result of gravitational compression during the period of the formation of Jupiter, then it is possible to find, as Taylor did, completely corresponding observational data values. The energy of Jovian gravitational compression equals $\sim 3 \cdot 10^{43}$ erg. If it accumulates in the core with specific heat $C \simeq 10^{8}$ erg/deg, then the temperature of the core must be of the order of $2 \cdot 10^{5}$°K and the initial temperature of the Jovian surface, about $2 \cdot 10^{3}$°K. Then in order to cool the Jovian surface from the initial temperature to a final value of 128-130°K in the case of convective heat transfer from the core through the mantle, approximately $3 \cdot 10^{9}$ years would be required /59 which shows good agreement with the assumed age of the planet.

R. Smoluchovsky [212] came to a similar conclusion after having examined the hydrogen-helium model of the internal structure of Jupiter with consideration for the equation of state of matter at very high pressures and temperatures.

V. G. Fesenkov believed [73] that the source of internal heat on Jupiter may be the decay of radioactive elements, including uranium and thorium. But in this connection if we assume that the radioactive substances are uniformly distributed over the entire thickness of the planet and that the prevalence of radioactive elements in all planets is approximately identical, the total radiation of radioactive heat from Jupiter would have to be approximately 300 times greater than for the earth, i.e., approximately $1.5 \cdot 10^{15}$ cal/sec. This corresponds to a heat flux from 1 cm^2 of the Jovian surface of $F'_{♃} = 1.02 \cdot 10^{2}$ erg/cm^{2}sec, which amounts in all to only about 1% of the observed value $F_{♃}$. It is necessary either to assume the presence of a significantly larger content of radioactive elements on Jupiter or to accept that the radioactive substances are concentrated mainly along the planetary surface, which coincides poorly with concepts concerning the internal structure of Jupiter. In fact it is difficult to understand how heavy elements may be supported in the upper layers of the hydrogen mantle of the planet.

We must acknowledge that for the present the origin of the excess thermal radiation of Jupiter remains unknown. It is probable necessary to examine several exothermic chemical reactions which may occur in the depths of the Jovian atmospheric layers under high pressure conditions. Thus, for example, the ammonia formation reaction

$$N_2 + 3H_2 \rightleftarrows 2NH_3$$

occurs during an electrical discharge and best of all at high pressure and is accompanied by the release of a comparatively high quantity of heat--11 Cal per 1 mole of ammonia. At pressures of 4-5 thousand atm the synthesis of ammonia may occur with a 100% yield even in the absence of a catalyst. Other reactions probably occur involving the formation of hydrocarbon and nitrogen-hydrogen compounds with the release of heat. But for the present it is difficult to evaluate their role in increasing the temperature of Jupiter since conditions in the depths of the atmospheric layers are unknown.

c) The possible role of the "greenhouse effect." Recently another possible explanation for excess Jovian thermal radiation has been discussed. When we calculate the balance of the Jovian radiation temperature, we assume that all the planetary thermal radiation passes into space. But absorption of thermal infrared radiation may occur in planetary atmospheres if a gas is located there with sufficiently intensive absorption bands in the region of maximum thermal planetary radiation (20-40 μ). While absorbing thermal radia- /60 tion which proceeds from the planetary surface the atmosphere is heated and becomes a radiator in the thermal range. Part of the atmospheric radiation passes into space but the infrared atmospheric radiation, which is directed downward toward the planetary surface, will in turn heat the lower atmospheric layers and the surface to a higher temperature. This is called the "greenhouse effect" and plays a significant role in the atmospheres of such planets as Venus and the earth.

Based on laboratory measurement data L. Trafton [94] assumes that the greenhouse effect may be caused by the presence in the Jovian atmosphere of molecular hydrogen. Under the influence of pressure rotational dipole transformations are induced which determine absorption by H_2 molecules of radiation in the range from ~8 to ~33 μ. According to Trafton's calculations the thickness of molecular hydrogen at 30 km-atm already possesses thermal nontransparence which is capable of providing the "greenhouse" effect. Unfortunately estimates of the H_2 content in the outer Jovian atmosphere are at the present time not very definite; therefore it would be premature to maintain that hydrogen itself is the main agent which developes a "greenhouse" effect on Jupiter.

Laboratory investigations also reveal that in the λλ 20-35 μ region comparatively strong absorption may be developed by ammonia while the magnitude of the absorption depends to a significantly degree on pressure. It is apparent from Figure 21, which shows transmission curves for an ammonia layer with an equivalent thickness of 12 m-atm, that absorption increases significantly with an increase in pressure. T. Owen and T. Walsh [95] directed attention to this circumstance and noted that although the temperature on Jupiter is lower than it would be under laboratory measurements, the pressure may be greater than 1 atm. Then NH_3 absorption would have to be less than /61 represented on the drawing.

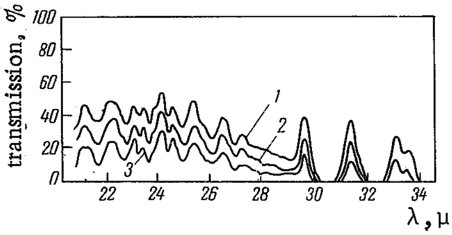


Figure 21. Radiation Transmission by a Layer of Ammonia is 12 m-atm at λλ 21-34 μ. NH_3 partial pressure 5 cm Hg, at nitrogen pressure N_2-0 cm Hg (1), 20 cm Hg (2) and 60 cm Hg (3) (After Owen and Walsh [95]).

The question of the magnitude of atmospheric pressure at the level of the surface cloud layer (P_0) has still not been solved and, strictly speaking, there is no basis for considering that $P_0 > 1$ atm. The NH_3 quantity in the external atmosphere, judging by spectral observational data rather less instead of greater than 7 m-atm. It is possible that the "greenhouse" effect is developed as a result of the effect of total absorption of thermal radiation by ammonia and by molecular hydrogen. However exact calculations of this effect are not possible without exact knowledge of the content of absorbent gases in the outer atmosphere.

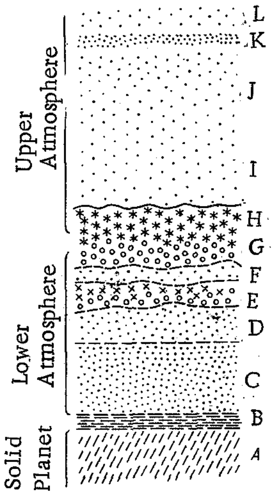
Clarification of the role of the "greenhouse" effect in increasing the temperature of the Jovian atmosphere has a great deal of significance in connection with the problem of atmospheric activity on Jupiter. If the "greenhouse" effect in fact may provide additional solar energy accumulations in the atmosphere of this planet then transient phenomena observed on the surface of the cloud layer may be examined from a different point of view than that adopted in the case where atmospheric heating occurs as a result of a flow of internal planetary heat. During the release of internal heat the most active transfer processes must occur in deep atmospheric layers; however on the surface of the clouds we observe only attenuated reflections of these processes. In a case where the basic role in the thermal conditions of Jupiter is played by the "greenhouse" effect, the deep atmospheric layers may remain in a more or less stable state. The "greenhouse" effect itself or the opacity of the Jovian atmosphere to thermal radiation may be varying due to diverse types of photochemical processes which occur in the upper atmosphere. Variability in the "greenhouse" effect in turn may cause for example, a change in the temperature gradient of the external atmosphere and of the upper cloud layer which will lead to the additional development of convective flows in the cloud layer. It is clear that in this connection variable phenomena on Jupiter must be closely associated with solar activity.

CHAPTER 3.

THE STRUCTURE OF THE ATMOSPHERE

§1. Simplified Models of the Vertical Structure of the Atmosphere

a) A diagram of the structure of the Jovian atmosphere. A rough diagram of the vertical structure of the Jovian atmosphere may be presented in the following manner (Figure 22). Above the solid or semi-liquid surface of the planet there is a region of very dense gas, under the influence of a high pressure, where the density may change very slowly with altitude, as we have seen previously. The tentative thickness of this region may be approximately 300-400 km. Above this is located the "normal" atmospheric region where density falls rather rapidly with altitude. In this part of the atmosphere the processes of the condensation of various gases and the formation of cloud layers may occur. We see the outer cloud layer as a surface of Jupiter. Tentatively we may assume that the thickness of the "normal" region of the atmosphere (to the outer cloud layer) amounts to approximately 200 km. Above the cloud cover of Jupiter is a transparent layer of outer atmosphere, either purely gaseous or containing a certain quantity of aerosol in the form of a light haze. It is this part of the atmosphere particularly which is accessible to direct observation both with the aid of optical and radioastronomical instruments. /6



(A) Solid planet
(B) Transition layer
(C) Intensively compressed gas
(D) Dry lower atmosphere
(E) Cloud layer of H_2O drops and crystals
(F) Dry atmosphere
(G) Clouds of NH_3 drops
(H) Outer cloud layer of NH_3 crystals
(I) Troposphere above the clouds
(J) Stratosphere
(K) Ionosphere
(L) Exosphere

Figure 22. An Approximate Diagram of the Vertical Structure of the Jovian Atmosphere.

The vertical structure of the atmosphere is construed to mean the distribution of temperature, pressure and density in the atmosphere, by altitude. For the planets, there is at the present time no possibility of carrying out independent observations of the distribution of all three parameters. Therefore in estimates of the vertical structure it is usually necessary to introduce specific assumptions concerning the nature of the temperature change with altitude, and to establish the specific chemical composition of the atmosphere or at least its mean molecular weight. Since all of these values are unknown at the present time it is possible to speak only of approximate models of the vertical structure of the Jovian atmosphere, and the choice between them may be made only with comparatively good agreement between observational data which satisfies one model.

The construction of a model of the Jovian atmosphere presents a more complex problem than, for example, the construction of a model of the Martian atmosphere. If such a model can be constructed for Mars, beginning with the planetary surface and going upward, since the temperature of the surface is known, then a model of the Jovian atmosphere must be constructed from the top downward, beginning at the highest atmospheric layers, since we have no observational data at all at our disposal concerning the properties of the Jovian surface itself, and we can only predict roughly conditions in the deep atmospheric layers while knowing only the properties and state of the upper layers. /63

Below we shall examine several simplified versions of atmospheric structure as applied to Jovian conditions. Their simplicity consists of the fact that first of all we establish a priori determinations of the law of temperature change with altitude or a definite form for the state of equilibrium in the atmosphere (of the entire atmosphere or of individual layers).

b) Initial data concerning the chemical composition for atmospheric models. We shall illustrate all further descriptions of the simplified models with calculations for four versions for the proposed quantitative chemical composition of the Jovian atmosphere (Table 3.1). We could select one preferred version but for the present there is still insufficient justification for this. In proposing one or another ratio between atmospheric constituents authors usually proceed from a basis of available observational data, and in addition, observe that with a given gas content the value obtained for the mean molecular weight is sufficiently close to the value derived from observations of the occultation of σ Arietis ($\overline{\mu} = 3.3$). This condition is well satisfied by the first three versions. Version I is based on Kuiper's model b, which we have already examined. Version II is the same model but with the gas content decreased by two times. This version represents an attempt to consider molecular absorption in the cloud layer which leads to exaggeration in quantitative estimates of gas content in the atmosphere above the clouds. /64

Version III is a model of the chemical composition proposed by Spinrad and Trafton [23]. According to their observations the quantity of molecular hydrogen in the outer atmosphere amounts to 27 ± 9 km-atm.

Finally Version IV is a model by Öpik [50]. We shall examine this model as an example with a significant preponderance of helium. As already pointed out earlier Öpik obtained $\overline{\mu} = 4.3 \pm 0.5$ from a recalculation of the results of observations of the occultation of σ Arietis. In this connection he also proposed a model of the chemical composition of the Jovian atmosphere with

$\bar{\mu} \approx 4$, which was more than 97% helium while the hydrogen fraction amounted to somewhat more than 2%.

TABLE 3.1. FOUR VERSIONS OF THE POSSIBLE QUANTITATIVE COMPOSITION OF THE JOVIAN ATMOSPHERE (GAS CONTENT IN THE OUTER ATMOSPHERE IN m-atm)

Gas	I	II	III	IV
H_2	$2{,}1 \cdot 10^4$	$7 \cdot 10^3$	$2{,}7 \cdot 10^4$	$5 \cdot 10^3$
He	$3{,}3 \cdot 10^4$	$1{,}1 \cdot 10^4$	$1{,}6 \cdot 10^4$	$2{,}1 \cdot 10^5$
CH_4	$1{,}5 \cdot 10^2$	50	$1{,}5 \cdot 10^2$	$1{,}5 \cdot 10^2$
NH_3	7	2,3	7	7
Ne	—	—	$1{,}4 \cdot 10^3$	$9 \cdot 10^2$
$\dot{\mu}$	3,26	3,26	3,35	4,02

Tr. Note--commas indicate decimal points.

c) The static equation of the atmosphere and the barometric formula. It is known from any course in meteorology (for example, see [98]) that if there is no vertical or horizontal displacement of gaseous masses in the atmosphere, the change in pressure with altitude is represented by the following equation:

$$dP = -\rho g dh, \tag{3.1}$$

where P is pressure; ρ is density; g is the acceleration of gravity; h is altitude calculated from a certain initial level (the planetary surface or the limit of the cloud layer). This equation is called the basic static equation of the atmosphere. In utilizing the ordinary gas equation of state /65

$$P = nkT = \rho \frac{R}{\mu} T, \tag{3.2}$$

where n is the number of molecules per unit volume, R is the gas constant, K is the Boltzmann constant, we may write the static equation of the atmosphere in the form

$$\frac{dP}{P} = -\frac{g\mu}{RT} dh; \tag{3.3}$$

and by integrating this equation within the limits from 0 to h, we obtain the so-called barometric formula in its general form:

$$P_h = P_0 e^{-\int\limits_0^h \frac{g\mu}{RT} dh'} . \tag{3.4}$$

By using this formula we may calculate how pressure changes with altitude in the atmosphere of a planet which is in hydrostatic equilibrium. But here it is necessary to define the function T(h), and also, if great altitudes are involved, to consider the change in the acceleration of gravity with altitude g(h). The latter may be disregarded for the lower Jovian atmosphere, and for the cloud layer and the zone of the outer atmosphere which is adjacent to it, since with an altitude limit up to 10^3 km acceleration g changes by not more than 2%. Significantly greater is the lateral effect of a change in g, caused first of all by centrifugal force which increases toward the equator. Therefore at the equator the effective acceleration g = 2,312 cm/sec^2, and at the pole g = 2,681 cm/sec^2, but for general calculations it is more correct to employ a certain intermediate value g = 2,450 cm/sec^2.

Density change with altitude is represented by the expression

$$\rho_h = \rho_0 \frac{T_0}{T_h} e^{-\int\limits_0^h \frac{g\mu}{RT} dh'}, \tag{3.5}$$

and the dependence of the number of gas molecules on altitude is expressed by a similar formula

$$n_h = n_0 \frac{T_0}{T_h} e^{-\int\limits_0^h \frac{g\mu}{RT} dh'} \tag{3.6}$$

Since a real change of temperature with altitude in a planetary atmosphere certainly cannot always be presented analytically the solution of equations (3.4) - (3.6) in a general form is not possible. Therefore in practice a number of assumptions are generally introduced which simplify calculations.

d) A homogeneous atmosphere. If we assume that density in the atmosphere /66 does not depend on altitude, i.e., $\rho(h) = \rho_1$ = const, from the static equation we obtain the expression

$$P_h = P_0 - \rho_1 g h, \tag{3.7}$$

which shows that in a homogeneous atmosphere the pressure drops linearly with altitude, where $P_h = 0$, when $\rho_1 gh = P_0$, i.e., a homogeneous atmosphere has a sharp limit which is situated at altitude

$$H = \frac{P_0}{\rho_1 g} = \frac{RT}{\mu g}. \tag{3.8}$$

This value H has the name the altitude of a homogeneous atmosphere or scale of altitudes. Although in fact we do not encounter a homogeneous atmosphere the concept of a scale of altitudes is very convenient for various calculations. The fact is that many optical properties of an atmosphere, for example, such as the transmission coefficient, refraction constant, optical thickness, etc. do not depend on density distribution by altitude. Under certain conditions it is also possible to assume that brightness of the light scattered by an atmosphere also does not depend on the form of the function $\rho(h)$, which significantly facilitates theoretical calculations of planetary reflectivity. We already used the value H while examining the refraction attenuation of star luminosity by the Jovian atmosphere.

A value similar to the altitude of a homogeneous atmosphere is used in order to obtain estimates of quantitative gas content in the planetary atmosphere. It is true that here as initial conditions we employ not the pressure and temperature on the planetary surface but "standard" conditions where $P_0 =$ $= 1$ atm and $T_0 = 273°K$.

The altitude of the homogeneous atmosphere above the surface of the cloud layer of Jupiter, if we accept $T_0 = 160°K$ as the temperature of the cloud surface, is shown below for the versions of chemical composition enumerated above:

Model	I	II	III	IV
H, km	16.6	16.6	16.2	13.4

Of course the temperature of the surface of the cloud layer is not really identical for all four models, but since the difference in temperatures cannot be more than 10-12% K the change in values H will not exceed 8%. Here again we must direct attention to the circumstance that the altitude of the homogeneous atmosphere, the mean molecular weight and the temperature are mutually related and that for the present there is no possibility of determining these values independently. The estimate of H, made by Baum and Code according to occultation observations of σ Arietis (H = 8.3 km) pertained not to the entire outer atmosphere, but only to that part of the atmosphere which was located under the atmospheric layer which effectively blocked the light of the star. The mean molecular weight determined by such observations depends on the temperature accepted for the effective occultation layer. /67

The term "scale height" is not an arbitrary one. The static equation of the atmosphere may also be written in the following form:

$$-\frac{dP}{P} = \frac{g\mu}{RT}dh = \frac{1}{H}dh, \qquad (3.9)$$

from which it can be seen that value $H = RT/g\mu$ may be employed as a unit of measurement in determining altitudes in any models of planetary atmospheres.

In a homogeneous atmosphere the temperature changes linearly with altitude. The temperature gradient equals

$$\frac{dT}{dh}=\frac{\mu}{\rho R}\frac{dP}{dh}=-\frac{\mu g}{R}. \qquad (3.10)$$

In such a case the vertical gradient for the Jovian atmosphere would amount to 9.7-11.8 deg/km, depending on the value μ accepted.

§2. The Stratosphere of Jupiter

a) The isothermal atmosphere. We shall begin our examination of the atmosphere of Jupiter not with the uppermost layers (the exosphere, the thermosphere and the ionosphere), but with the approximate isothermal region in which the concentration of atoms and molecules is sufficiently high to permit us to assume the fulfillment of radiation equilibrium conditions. The higher amd more rarefied layers, in which the temperature and density are determined first of all by photochemical processes and by absorption of far-ultraviolet and X-ray radiation of the sun, at the present time are practically inaccessible to optical investigations. Our concepts concerning these may be based only on purely speculative conclusions if we do not consider certain information obtained by means of radio astronomical observations.

In an isothermal atmosphere the temperature is identical at all altitudes so that a change of pressure and density with altitude is described by the simple formulas

$$P_h=P_0e^{-\frac{g\mu}{RT}h}=P_0e^{-h/H}; \qquad (3.11)$$

$$\rho_h=\rho_0e^{-\frac{g\mu}{RT}h}=\rho_0e^{-h/H}. \qquad (3.12)$$

Since as we shall see in an isothermal atmosphere density falls with altitude in accordance with an exponential law, it is clear that the atmosphere cannot have a sharp limit but extends over a great distance, with a gradual transition to the interplanetary medium. At altutude h = H in an isothermal atmosphere, /68
in contrast to a homogenous atmosphere, the pressure is not equal to zero but only to e times less than the pressure at the base of the atmosphere. It may be assumed that isothermality in the Jovian atmosphere must be observed in a region where there is no intensive, turbulent and convective displacements and where the atmosphere is in a state of radiation equilibrium.

b) Radiative equilibrium and the temperature of the Jovian stratosphere. We shall examine approximate transfer equations for radiant energy in the Jovian stratosphere, by employing a simple method described for the earth's atmosphere in [98]. We shall assume that thermal radiation in the atmosphere is not scattered. Then we can disregard the diffuse component and examine only the monochromatic radiation flux directed downward (G_λ) and upward (U_λ). The downward current G_λ, in passing through a certain elementary layer dh, is attenuated by the quantity $k_\lambda \rho G_\lambda dh$, where k_λ is the absorption coefficient and ρ is the absorbent gas density. At the same time current G_λ, in passing through the same layer, is increased by the quantity $e_\lambda \rho dh$, which represents the intrinsic thermal radiation of this layer (e_λ is the emission coefficient). Then the total flux change during the transmission of the layer downward ($dh < 0$) will be

$$dG_\lambda = k_\lambda \rho G_\lambda dh - e_\lambda \rho dh. \qquad (3.13)$$

If we assume that in the atmosphere Kirchoff's law is fulfilled (i.e., $e_\lambda = k_\lambda B_\lambda$ (B_λ is a Planck function), then by introducing the mass element of the gas $dm = \rho dh$, we obtain

$$\frac{dG_\lambda}{dm} = k_\lambda (G_\lambda - B_\lambda). \qquad (3.14)$$

This is also an approximate transfer equation for monochromatic thermal radiation which passes into the interior of the atmosphere. For the inverse flux U_λ (emergent radiation) we obtain the transfer equation by a similar method

$$\frac{dU_\lambda}{dm} = k_\lambda (B_\lambda - U_\lambda). \qquad (3.15)$$

Now we shall assume that the absorption coefficient of thermal radiation does not depend on wavelength (a grey atmosphere). Without such an assumption the elementary solution of the radiative transfer equation is not possible. Otherwise a solution would be rather complex, although it would not fundamentally change the result desired.

A state of radiation equilibrium means that at any level in an atmospheric zone under consideration the quantity of absorbed and emitted radiation is equal, i.e.,

$$kG + kU = 2kB \qquad (3.16)$$

or

$$G + U = 2B. \qquad (3.17)$$ /69

If we consider transfer equation (3.14) and (3.15) it is easy to show that

$$U - G = F_r = \text{const}. \qquad (3.18)$$

This means that the effective flow of thermal radiation F_r, which corresponds to the difference in the ascending and descending currents, is constant with respect to altitude in the stratosphere where radiation equilibrium occurs. Then

$$\frac{d}{dm}(G + U) = -kF_r, \qquad (3.19)$$

from which

$$G + U = -kF_r m + C. \tag{3.20}$$

At the upper boundary of the atmosphere ($m = m_\infty$) $G = 0$ and $U = F_r$. Then the ingration constant will equal

$$C = F_r\,(1 + km_\infty). \tag{3.21}$$

Then we may write

$$G + U = F_r\,[1 + k\,(m_\infty - m)] = 2B = 2\sigma T^4. \tag{3.22}$$

Since we may consider for the stratospheric boundary that $m = m_\infty$,

$$\sigma T^4 \simeq \frac{1}{2} F_r. \tag{3.23}$$

From this it is not difficult to find the temperature of the stratosphere. On the average we may consider that heat loss per unit surface of the Jovian atmosphere is equal to the flow of thermal energy from the sun less reflected radiation. The effective influx of solar energy equals

$$S = \frac{S_0}{4}(1 - A), \tag{3.24}$$

where S_0 is the solar constant; A is the albedo of the planet. This means that

$$\sigma T^4 = \frac{1}{2} F_r = \frac{1}{2} S. \tag{3.25}$$

If we assume that $A = 0.45$, then $T_{st} = \sqrt[4]{S/2\sigma} \simeq 90°K$.

Based on several different considerations Kuiper obtained a stratospheric temperature of 86°K. All of the calculations shown are made on the assumption that the stratospheric temperature is determined exclusively by the absorption of solar radiation. However, as already mentioned above, the flow of radiation which emanates from Jupiter exceeds the influx of solar energy by almost 2.4 times. This means that we must calculate the temperature of the stratosphere with consideration for this excess radiated energy. Since in this case /70

$$\sigma T^4 = 2{,}36 \cdot \frac{1}{2} F_r = 2{,}36 \cdot \frac{1}{2} S, \tag{3.26}$$

the temperature of the stratosphere of Jupiter will be equal to $T_{st} = 90\sqrt[4]{2.36} \approx$

Öpik [50] undertook an extremely detailed analysis of radiation processes in the stratosphere of Jupiter and considered the differences in absorptivity in the various spectrum intervals, including absorption by methane and ammonia both in the infrared as well as in the ultraviolet region of the spectrum. He examined four versions, which differed according to the degree of effectiveness of atmospheric heating during molecular absorption of radiation. The fact is that not all radiation absorbed by molecules is transformed into atmospheric thermal energy. A part of the absorbed quanta is spontaneously radiated by an excited molecule and does not contribute to atmospheric heating. Opik obtained an almost identical stratospheric temperature for all four versions, on the average equal to $T_{st} = 116°K$.

Having assumed that the ratio of the temperature of the stratosphere in the temperature of the surface of the cloud layer on Jupiter to be the same as on the earth ($T_{st}/T_{sur} = 0.68$), Öpik found still another stratospheric temperature value of $T_{st} = 106°K$.

Thus different methods of calculating the temperature of the stratosphere of Jupiter lead to rather close values, so that on the average we may accept that with an excess of thermal radiation for Jupiter $T_{st} = 108 \pm 5°K$. Now we may also calculate several other parameters of the stratosphere which depend on temperature.

c) Pressure distribution in the stratosphere. Using the versions for the chemical composition of the Jovian atmosphere introduced previously, we shall calculate first of all the scale heights (in km) for the stratosphere where T_{st} = 108 and 88°K (without considering excess thermal planetary radiation):

Model	I	II	III	IV
$T_{st} = 108°K$	11.2	11.2	10.6	9.1
$T_{st} = 88°K$	9.1	9.1	8.9	7.4

The pressure change law with altitude in the stratosphere is

$$P = P_1 e^{-h/H_{st}}. \qquad (3.27)$$

Since the pressure at the base of the stratosphere is not known, it is convenient to present (3.27) in logarithmic form

$$\log P = \log P_1 - 0{,}434 \frac{h}{H_{st}} \qquad (3.28)$$

and to calculate the logarithmic pressure gradient d log P/dh (for 1 km of altitude): /71

Model	I	II	III	IV
T_{st} = 108°K	0.039	0.039	0.041	0.048
T_{st} = 88°K	0.048	0.048	0.049	0.058

It is possible to attempt a very rough determination of the value of pressure (P_1) at the base of the stratosphere if we assume that ammonia is near saturation at least up to the altitude of the tropopause, i.e., to the lower limit of the stratosphere. Using Table 2.1, we find the NH_3 saturated vapor pressure at temperatures 108 and 88°K which we relate to the level of the lower limit of the stratosphere, considering the partial pressure of ammonia at this level. The pressure will equal:

$$P_a = 9{,}95 \cdot 10^{-3}\ \text{dyne/cm}^2 (T_{st} = 108^\circ\text{ K});$$
$$P_a = 3{,}55 \cdot 10^{-6}\text{dyne/cm}^2\ (T_{st} = 88^\circ\text{ K}).$$

If there is no significant stratification of various atmospheric components near the tropopause, i.e., the gases are fully mixed, we may find the upper limit of the total pressure at the level of the tropopause for a given model of the chemical composition of the atmosphere:

$$P_1 = P_a\left(1 + \sum \frac{N_i}{N_a}\frac{\mu_i}{\mu_a}\right) = P_a\left(1 + \frac{L_i}{L_a}\sum\frac{\mu_i}{\mu_a}\right), \tag{3.29}$$

where N_i is the number of molecules of each atmospheric component in a vertical column of unit section above the level of the tropopause; μ_i is the molecular weight; L_i is the equivalent height of a gas column which corresponds to the gas content in the atmosphere.

Shown below is the upper pressure limit P_1 (in dyne/cm^2) for the base of the Jovian stratosphere: /72

Model	I	II	III	IV
T_{st} = 108°K	14.8	14.8	12.5	74.5
T_{st} = 88°K	0.0052	0.0052	0.0044	0.0260

This of course is only a rough approximation of pressure values which illustrate conditions in the Jovian stratosphere only to a certain degree (Figure 23). Calculations reveal that the stratospheric region is accessible to penetration by short-wave solar radiation so that photochemical reactions, accompanied by absorption or by the release of energy, may occur throughout the entire depth of the stratosphere. Therefore isothermal conditions can hardly exist in the real stratosphere of Jupiter. It is more probable that there are one or more layers of temperature inversion in the stratosphere, as a result of which pressure change with altitude has a more complex nature.

§3. The Tropospheric Zone of Jupiter Above the Clouds (Dry Adiabatic Models).

a) A polytropic and adiabatic atmosphere. It may be thought that above the surface of the cloud layer the convection transfer processes do not cease abruptly, but occupy a certain altitude zone in the atmosphere. It is true that S. Gross and S. Rasool [96] completed their calculations of temperature distribution in the outer Jovian atmosphere under the assumption that the atmosphere was in a state of radiation equilibrium from the surface of the cloud layer itself. But in their calculations they used too many arbitrary values so that their model of the outer atmosphere bears an extremely arbitrary nature. It is however more probable that the region of radiant equilibrium and isothermy in the Jovian atmosphere begins at a certain altitude h_{st} above the surface of the cloud layer (the altitude of the tropopause). Below the tropopause is located a convection atmospheric zone in which thermal energy transfer is accomplished basically as a result of convection.

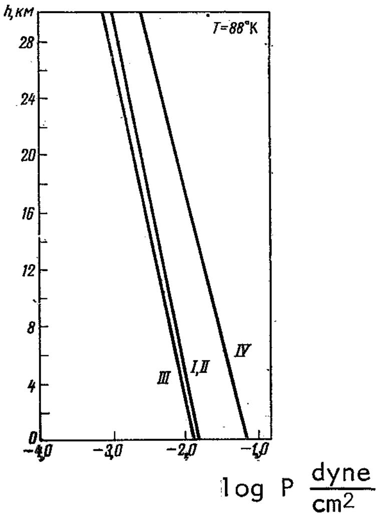


Figure 23. Pressure Change (in dyne/cm^2) with Altitude in the Stratosphere of Jupiter where T = 88°K. The numbers near the lines designate different models for the chemical composition of the atmosphere (see Table 3.1).

An atmosphere in which the temperature changes linearly with altitude is called a polytropic atmospheric. For this atmosphere

$$T = T_0 - \Gamma h, \tag{3.30}$$

where $\Gamma = -dT/dh$ is the vertical temperature gradient. Let us recall the static equation of the atmosphere (3.3). In the case of a polytropic atmosphere this equation will assume the form

$$\frac{dP}{P} = -\frac{g\mu dh}{RT} = -\frac{g\mu dh}{R(T_0 - \Gamma h)} = \frac{g\mu}{R\Gamma}\frac{dT}{T}. \tag{3.31}$$

By integrating this equation within limits P_0 to P_h and T_0 to T_h (g is considered a constant), we obtain /73

$$\ln\frac{P_h}{P_0} = \frac{g\mu}{R\Gamma}\ln\frac{T_h}{T_0} \tag{3.32}$$

or

$$P_h = P_0\left[\frac{T_h}{T_0}\right]^{g\mu/R\Gamma} = P_0\left[1 - \frac{\Gamma h}{T_0}\right]^{g\mu/R\Gamma}. \tag{3.33}$$

Formula (3.33) makes it possible for us to calculate the pressure distribution in a polytropic atmosphere if the temperature gradient Γ is known. The adiabatic atmosphere is a particular case in which pressure and density changes with atmosphere occur without additional absorption or release of heat. If in such an atmosphere a certain gas mass ascended, then its expansion in proportion to the increase in altitude would be accompanied by a decrease in temperature without transmission of part of the heat to the surrounding gas (adiabatic expansion). In the troposphere of Jupiter, where there are no intrinsic sources of thermal energy, the temperature and pressure must change with altitude in accordance with the adiabatic law, although, of course, certain deviations in the adiabatic process may occur. But with significant deviations from the adiabatic law, the troposphere would be either extremely stable, so that there would be no vertical motion in it, or, on the other hand, we would observe an extremely unstable atmosphere. In the first case it would be strange to observe the phenomenon of bright and dark formations in the cloud cover of the planet, which are certainly associated with convective transfer; in the second case we would observe sharp fluctuations of the height of the limit of the cloud layer in various planetary zones.

It is known that during the adiabatic process the ratio between the pressure and the temperature is expressed by the Poisson equation

$$\frac{T}{T_0} = \left(\frac{P}{P_0}\right)^{\frac{\gamma-1}{\gamma}}, \tag{3.34}$$

where $\gamma = C_p/C_V$ is the ratio of specific heat capacities of the gas at constant pressure and constant volume, which for a given gas is a constant which is dependent only on the number of degrees of freedom in the molecule. If equation (3.34) is differentiated and we introduced dh in place of dP, by utilizing the relationship already known

$$dP = -\rho g dh = -\frac{P}{RT} g\mu dh, \tag{3.35}$$

then it is not difficult for us to find the expression for the adiabatic vertical temperature gradient

$$\Gamma_a = -\frac{dT}{dh} = \frac{g\mu}{R}\frac{\gamma-1}{\gamma}. \tag{3.36}$$

This is the so-called dry adiabatic gradient which must occur in the atmosphere /74 if the atmosphere contains no saturated vapors and if condensation of vapors or evaporation of drops and crystals of frozen gases does not occur. On the basis of the models of the chemical nature of the Jovian atmosphere accepted, it is easy to determine the value of the temperature gradient for the troposphere above the Jovian cloud layer. In this connection we must naturally introduce into (3.36) average values $\bar{\gamma}$ and $\bar{\mu}$, consisting of a mixture of gases which make up the Jovian atmosphere. The values C_p and γ are given in Table 3.2 for components of the Jovian atmosphere.

TABLE 3.2. SPECIFIC HEAT CAPACITY C_p AND PARAMETER γ FOR BASIC COMPONENTS OF THE JOVIAN ATMOSPHERE

Gas	C_p,cal/g·deg	γ	Gas	C_p,cal/g·deg	γ
Hydrogen	3,409	1,45	Ammonia	0,536	1,34
Helium	1,251	1,66	Neon	—	1,64
Methane	0,593	1,31			

Tr. Note--commas indicate decimal points.

Kuiper [3] made the first adiabatic temperature gradient calculation for the Jovian atmosphere. For model b he found a value of $\Gamma_a = 3.75$ deg/km at $\bar{\gamma} = 1.56$ and $\bar{\mu} = 3.26$. Dry adiabatic temperature gradients are given in Table 3.3 for four models of the chemical composition of the Jovian atmosphere.

TABLE 3.3. DRY ADIABATIC TEMPERATURE GRADIENT IN THE ATMOSPHERE OF JUPITER ABOVE THE CLOUDS

Model	$\bar{\mu}$	$\bar{\gamma}$	Γ_a,deg/km	Model	$\bar{\mu}$	$\bar{\gamma}$	Γ_a,deg/km
I	3,26	1,56	3,44	III	3,35	1,50	3,28
II	3,26	1,56	3,44	IV	4,02	1,66	4,70

Tr. Note--commas indicate decimal points.

As the Table shows in the Jovian troposphere above the clouds the temperature falls by approximately 3-4°K for every km of altitude. The dry adiabatic gradient in the troposphere of the earth is approximately equal to 10 deg/km.

Knowing the temperature gradient we may calculate the pressure and density behavior with altitude in the Jovian troposphere. But first it is necessary to establish the total pressure and density values at the initial level, i.e., at the surface of the Jovian cloud layer. /7

b) Pressure and density at the upper limit of the cloud layer (theoretical evaluations). The total atmospheric pressure at the level of the limit of the cloud layer will equal

$$P_0 = \sum P_i = \sum m_i g, \tag{3.37}$$

where P_i represents partial pressures of atmospheric components; m_i is the mass of each of the gas components in an atmospheric column of unit section. This mass is determined in accordance with the formula

$$m_i = \frac{L_i \mu_i}{V_0}, \quad (3.38)$$

where L_i is the equivalent thickness of a layer of given gas under normal conditions (in cm-atm); V_0 = 22,400 cm^3, the volume of 1 gram-molecule of gas. The values of the partial pressures of each gas component of the atmosphere, the total pressure (P_0) and density (ρ_0) at the upper limit of the cloud cover for four models are shown in Table 3.4.

TABLE 3.4. PARTIAL PRESSURES (in dynes/cm^2), TOTAL PRESSURE (in dynes/cm^2) AND DENSITY (g/cm^3) OF THE ATMOSPHERE AT THE UPPER LIMIT OF THE CLOUD LAYER

Gas	I	II	III	IV
		P_i, dyne/cm^2		
H_2	$4,59 \times 10^5$	$1,53 \times 10^5$	$5,90 \times 10^5$	$1,09 \times 10^5$
He	$4,44 \times 10^6$	$4,80 \times 10^5$	$7,01 \times 10^5$	$9,19 \times 10^6$
CH_4	$2,62 \times 10^4$	$8,82 \times 10^3$	$2,62 \times 10^4$	$2,62 \times 10^4$
NH_3	$1,30 \times 10^3$	$4,16 \times 10^2$	$1,30 \times 10^3$	$1,30 \times 10^3$
Ne	—	—	$3,06 \times 10^5$	$1,97 \times 10^5$
		P_0, dyne/cm^2		
	$1,93 \times 10^6$	$6,42 \times 10^5$	$1,62 \times 10^6$	$9,52 \times 10^6$
		ρ, g/cm^3		
	$4,72 \times 10^{-4}$	$1,51 \times 10^{-4}$	$4,09 \times 10^{-4}$	$2,88 \times 10^{-3}$

Tr. Note--commas indicate decimal points.

The first three models on the whole give similar results; the total pressure obtained equals 1.9 atm (I), 0.6 atm (II) and 1.6 atm (III). Model IV leads to a value P_0 = 9.5 atm. It would be very important to compare these theoretical results with observations. For the present, unfortunately, there are practically no observational data in this area. An attempt at the spectral determination of the atmospheric pressure on Jupiter will be described in the next section.

c) Observational estimates of atmospheric pressure. The total pressure near the limit of the Jovian cloud layer may be found approximately through /76 measurements of the widths of the rotational lines in the absorption bands of methane and ammonia if we apply to them the usual theory of the contour and intensity of atomic absorption lines.

We know from theory (see, for example, [99], [100]), that spectral absorption lines are broadened as a result of the Doppler effect, which is a change in absorption wavelength for atoms in motion along the line of sight and also as a result of the attenuation of vibrations from the oscillator linked with the finiteness of time and with atomic collisions. Doppler broadening also depends on temperature which determines the limits of the effective velocities of atoms and molecules. The Doppler line halfwidth equals

$$\Delta\lambda_a = 2\sqrt{\frac{2\lambda_0^2 kT}{Mc^2}} = 7{,}16\cdot10^{-7}\lambda_0\sqrt{T/\mu}, \tag{3.39}$$

where M is the atomic or molecular mass; μ is the atomic or molecular weight; c is the velocity of light; λ_0 is the wavelength of the line center (in the Å). As usual the name halfwidth of a line is given to the distance between points on the contour of the radiation or absorption line in which intensity is equal to half of the intensity within the center of the line.

The line halfwidth which is determined by the collision of absorbent atoms (or molecules) with atoms (or molecules) of another gas is called the Lorentz halfwidth and is represented by the following formula (in frequencies):

$$\Delta\nu = 2\sigma^2 N_A\sqrt{\frac{2}{\pi R}\left(\frac{1}{\mu_1}+\frac{1}{\mu_2}\right)}\frac{P}{\sqrt{T}}, \tag{3.40}$$

where σ is the radius of the effective collision section; N_A is the Avogadro number; R is the gas constant; P is pressure; μ_1, μ_2 are the molecular weights of the colliding gas atoms in the mixture. Thus the Lorentz halfwidth is proportional to the value of the pressure and inversely proportional to $\sqrt{T}$.

With a temperature at the limit of the cloud layer of 160°K the Doppler halfwidth for lines in the CH_4 absorption band at 6190 Å will equal $\Delta\lambda = 7.16\cdot10^{-7}\cdot6.19\cdot10^{3}\cdot3.16 \simeq 0.014$ Å. Thus the halfwidth of the absorption lines in the Jovian spectrum must be very small so that the line contour may be considered to be caused mainly by the attenuation of vibrations of the oscillators as a result of collisions, i.e., by Lorentz attenuation.

Based on these considerations, Spinrad and Trafton [23] made an attempt to determine the upper limit with a total pressure above the cloud layer of Jupiter according to the width of lines in the CH_4 band at 6190 Å by measuring one of the spectrograms of the planet which had a dispersion of 3.3 Å/mm. On the average the halfwidth proved to be $\Delta\lambda \leqslant 0.03$ Å which in wave /77 numbers amounts to $\Delta\nu \leqslant 0.08$ cm^{-1}. Under normal conditions (T_n = 300°K, P_n = 1 atm) the halfwidth $\Delta\nu'$ of CH_4 lines in the mixture with helium and molecular hydrogen equals approximately 0.04 cm^{-1}. Then from formula (3.40) it is clear that the pressure in the Jovian atmosphere may be determined by utilizing the simple relationship

$$\frac{P_J}{P_n} = \frac{\Delta\nu'_J}{\Delta\nu'_n}\sqrt{\frac{T_J}{T'_n}}. \tag{3.41}$$

The value P_J still cannot be considered to be pressure at the surface of the cloud layer. In fact observable absorption lines are formed in the atmosphere of Jupiter at various levels, i.e., under various pressures and temperatures. Therefore we shall observe a certain effective line intensity which corresponds to absorption by molecules located in the atmospheric column along the line of sight. Correspondingly temperature T_J must not be the temperature of the surface of the cloud layer, but rather the temperature of a certain effective atmospheric level. Since we are concerned here with the upper limit of pressure, we may accept $T_J = 150°K$. Then we obtain $P_J \leqslant 1.4$ atm and as Spinrad and Trafton believe, $P_0 \leqslant 2.8$ atm at the surface of the cloud layer. Apparently this value actually represents the upper limit of the atmospheric pressure at the surface of the cloud cover of Jupiter, which gives us the right to select as noncontradictory the observational results of the first three models only of the chemical composition of the atmosphere. Öpik's model, according to which the pressure must be greater than 9 atm, currently does not correspond to observational data since in this case $\Delta\nu'_J$ would be equal to ~ 0.24 cm^{-1}.

On the other hand the value 2.8 atm may be considered to be close to the actual pressure at the surface of the cloud layer only in a case where the effective level of the formation of the CH_4 absorption lines are situated above the cloud limit. However, as we have already noted in the preceding chapters, absorption by methane molecules occurs to a significant extent within the cloud layer so that the effective level of the line formation may lie near the surface of the clouds and even at a certain depth below this surface. Then the pressure at the surface of the cloud layer will not be greater but will be less than the value P_J, since $P_0 < 1$ atm, which agrees with the pressure estimate in model II.

On spectrograms of Jupiter with a dispersion of 3.3 Å/mm, J. Beckman [206] measured halfwidths of the CH_4 lines in the CH_4 absorption band at 6,190 Å which proved to equal 0.04 Å with a possible error of 15%. According to this width he found the effective pressure value to be 1.16 atm. For the cloud layer for absorption only in the outer atmosphere $P_0 \cong 2.3$, but if the absorption lines form in the cloud layer then again we find that $P_0 < 1$ atm. Apparently the value $P = 1$ atm may be considered as /78
the upper limit of the pressure at the surface (or at the arbitrary upper limit) of the Jovian cloud layer.

d) Pressure change with altitude in the troposphere above the clouds. Pressure dependence on altitude in the adiabatic troposphere is determined by the same formula which was introduced for a general case of a polytropic atmosphere

$$P = P_0\left[1 - \frac{\Gamma_a h}{T_0}\right]^{\frac{g\mu}{R\Gamma_a}}, \qquad (3.42)$$

For the four models of the chemical composition this dependence may be written in logarithmic form which is convenient for rapid calculations with the substitution of appropriate numerical values (P in atm, h in km):

$$\begin{aligned} &\text{I. } \log P = 0{,}28 + 2{,}79 \log(1 - 0{,}021h),\\ &\text{II. } \log P = -0{,}19 + 2{,}79 \log(1 - 0{,}021h),\\ &\text{III. } \log P = 0{,}21 + 3{,}01 \log(1 - 0{,}020h),\\ &\text{IV. } \log P = 0{,}98 + 4{,}02 \log(1 - 0{,}029h). \end{aligned} \qquad (3.43)$$

Corresponding curves of the log P change with altitude are shown in Figure 24. The temperature at the surface of the clouds is taken to equal 160°K. Certain deviations from this value in various models do not play a significant role. We are reminded that these considerations are valid only for a dry atmosphere in which the processes of condensation and evaporation do not occur. But we cannot exclude the possibility that there may also be moist atmosphere above the basic cloud layer, so that either ammonia is close to a state of saturation, which we assumed in a number of cases in order to simplify calculations, or even condensation of ammonia and other chemical compounds might occur in the outer atmosphere with the formation of light haze from crystals.

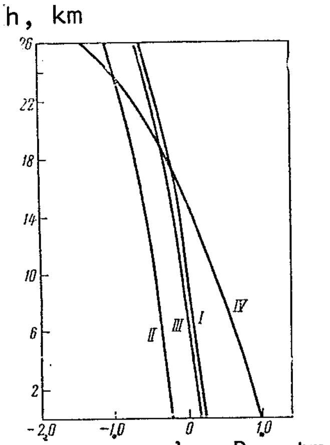


Figure 24. Pressure Change with Altitude in the Jovian Troposphere Above the Cloud [see (3.43)].

§4. Wet Adiabatic Models of the Jovian Troposphere /7

a) The sublimation of ammonia. Of all the known components of the Jovian atmosphere only ammonia may be in various aggregate states in the upper atmosphere of Jupiter. The NH_3 solidification point is 196°K (-77°C), while the temperature at the cloud limit is at least 30-35° lower. The boiling points of hydrogen, methane and helium are significantly lower than the temperature of the cloud layer and in the outer atmosphere these gases cannot condense due to the fact that the partial pressures there are considerably lower than the required saturated vapor pressures. Therefore an atmosphere which consists of these gases may be considered as a dry atmosphere. Ammonia itself in the thermodynamics of the Jovian atmosphere plays approximately the same role that water vapor plays in the atmosphere of the earth.

If in a given region of the atmosphere conditions are favorable for the condensation of ammonia then in such a "wet" atmosphere the vertical temperature gradient must be less than the adiabatic gradient in a dry atmosphere. If, for example, a certain mass of "wet" air is displaced upward and is cooled then a part of the ammonia may condense and in the process of condensation it may, as is known, release latent heat which partially balances the temperature reduction of the gas mass. Therefore a drop in temperature with altitude will occur more slowly than in a dry atmosphere. The difference between the "dry adiabatic" and "wet adiabatic" temperature gradients will depend on the value of ammonia concentration or on specific "humidity." The latter equals

$$q=\frac{m_a}{m_d+m_a}=\frac{\rho_a}{\rho_d+\rho_a}, \tag{3.44}$$

where m_a and ρ_a are the mass and density of ammonia; m_d and ρ_d are the mass and density of a "dry" gas. In a unit volume of "wet atmosphere" with temperature T and pressure P, if the partial pressure of the ammonia equals e_a, the "dry gas" fraction of the pressure is $P - e_a$. Then

$$q=\frac{\frac{e_a\mu_a}{RT}}{\frac{(P-e_a)\mu_d}{RT}+\frac{e_a\mu_a}{RT}}=\frac{e_a\frac{\mu_a}{\mu_d}}{P+\left(\frac{\mu_a}{\mu_d}-1\right)e_a}. \tag{3.45}$$

If $\mu_d = 3.3$, then

$$q=\frac{5{,}15e_a}{P+4{,}15e_a}. \tag{3.46}$$

Since even for saturated vapors of ammonia ($e_a = P_a(T)$), the pressure is /80
much less than total pressure (the limit of the cloud layer, for example, $P_a/P \simeq 10^{-3}$), we may consider as an approximation that

$$q\simeq 5{,}15\frac{e_a}{P}. \tag{3.47}$$

In the region of the cloud layer surface $q \simeq 0.005$.

It is most probable that under low temperature conditions in the outer atmosphere and in the upper part of the cloud layer we shall have to deal with two states of ammonia--the gaseous and the solid. The transition from one state to another may occur by means of sublimation without transformation to the liquid state. This is possible, of course, only if $e_a \approx P_a(T)$, while where $e_a \ll P_a(T)$ the atmosphere may be considered "dry."

b) The wet adiabatic vertical temperature gradient. We shall examine in detail the moist adiabatic process in order to clarify the extent of the difference in the temperature gradient for the "dry" and "wet" atmosphere. Here it is necessary to keep two possible versions in mind: the "wet" atmosphere, in which sublimation does not occur, and the "wet" atmosphere which contains ammonia in the solid phase (the cloud layer, haze).

If NH_3 vapors do not reach a saturated state the adiabatic energy flux equation may be written in the following form:

$$dQ_1 + dQ_2 = 0, \tag{3.48}$$

where dQ_1 is the quantity of heat received by the "dry" gas mixture; dQ_2 is the quantity of heat received by ammonia. Since in a "wet" mixture with temperature T_1, q ammonia vapors are present in (1 - q) "dry" gas mixtures, we may write, in agreement with [98]:

$$dQ_1 = C_{pd}(1-q)dT_1 - \frac{RT_1}{\mu_d}(1-q)\frac{d(P-e_a)}{P-e_a}; \tag{3.49}$$

$$dQ_2 = C_{pa}\,qdT_1 - \frac{RT_1}{\mu_a}q\frac{de_a}{e_a}. \tag{3.50}$$

These are the same equations which are employed for the earth's atmosphere in meteorology courses. The difference consists only in substituted values which correspond not to water vapor but to ammonia.

If during the ascent of a mass of "wet" gas an increase or a decrease in specific humidity does not occur, i.e., if q = const, then

$$\frac{dq}{q} = \frac{de_a}{e_a} - \frac{dP}{P} = 0, \tag{3.51}$$

and since $e_a \ll P$, and /81

$$\frac{d(P-e_a)}{P-e_a} = \frac{dP}{P}, \tag{3.52}$$

then with (3.48) we have

$$C_{pd}\left(1-q+\frac{C_{pa}}{C_{pd}}q\right)dT_1 - \frac{RT_1}{\mu_d}\left(1-q+\frac{\mu_d}{\mu_a}q\right)\frac{dP}{P} = 0 \tag{3.53}$$

In connection with the four versions of the chemical composition of the Jovian atmosphere which we examined previously, the values C_{pa}/C_{pd} and μ_d/μ_a are contained within relatively narrow limits:

$$0.275 \leqslant \frac{C_{pa}}{C_{pd}} \leqslant 0.390, \quad \frac{C_{pa}}{C_{pd}} \simeq 0.3$$

and

$$0{,}185 < \frac{\mu_d}{\mu_a} < 0{,}235, \quad \frac{\mu_d}{\mu_a} \simeq 0{,}2.$$

Therefore equation (3.53) may be reduced to the following form:

$$\frac{dT_1}{T_1} = \frac{R}{\mu_d C_{pd}} \frac{1-0{,}8q}{1-0{,}7q} \frac{dP}{P}. \tag{3.54}$$

After utilizing the static equation (3.3), we obtain

$$\frac{dT_1}{dh} = -\frac{g}{C_{pd}} \frac{1-0{,}8q}{1-0{,}7q} \frac{T_1}{T}, \tag{3.55}$$

where T is environmental temperature. Since the temperature difference between the mass of "wet" gas mass and the environment may be disregarded and since at low q ($q < 10^{-2}$) we may consider that the second factor in (3.55) differs very little from unity, we obtain the same formula from (3.55) which shows the dry adiabatic temperature gradient:

$$\frac{dT}{dh} = -\frac{Ag}{C_p} = -\frac{1}{R} \frac{\gamma-1}{\gamma} g\mu = -\Gamma_a. \tag{3.56}$$

Thus if sublimation of ammonia does not occur in that part of the Jovian troposphere above the clouds, then the vertical temperature gradient must remain practically equal to the dry adiabatic gradient even where ammonia is near a state of saturation.

The matter is different in a case when in an atmosphere saturated with ammonia vapors, condensation occurs, at which time latent heat of vaporization L is released, and if liquid ammonia is transformed into crystals, latent heat of fusion L' is released. When the products of condensation remain suspended /82
in the atmosphere without leaving the gas volume under consideration, the process of phase transformations is reversible: in evaporating, the condensation products fill the volume with vapor and absorb the same quantity of heat which was released during condensation. Such a process is called a wet adiabatic process. For this process a term is added to the thermal energy flux equation which corresponds to the quantity of heat released during the condensation of quantity dq of NH_3 vapors:

$$dQ = C_p dT - \frac{RT}{\mu} \frac{dP}{P} + (L + L')\,dq. \tag{3.57}$$

Since dQ = 0 for the adiabatic process, in the final analysis we shall obtain the following approximate formula for the wet adiabatic temperature gradient:

$$\Gamma_{ma} = \frac{g}{C_p}\frac{P+a}{P+b} = \Gamma_a \frac{P+a}{P+b}, \tag{3.58a}$$

where

$$a = 5{,}15\frac{(L+L')P_a\mu}{RT} \text{ and } b = 5{,}15\,\frac{L+L'}{C_p}\,\frac{dP_a}{dT}. \tag{3.58}$$

This formula is valid for comparatively small values q, which also occur in the Jovian atmosphere. The differences between the "moist" and "dry" adiabatic gradients are very small for the models of the chemical composition of the atmosphere which we have already examined. Thus, in substituting, for example, in (3.58) data for model I, we obtain instead of Γ_a = 3.44 deg/km the value Γ_{ma} = 3.14 deg/km. It is true that in these models the relative content of ammonia amounts to less than 0.001. Naturally in this connection the role of ammonia in the thermal conditions of the atmosphere is quite insignificant. This is also confirmed by more careful and detailed calculations accomplished in 1963 by B. Lasker [52]; this data will be discussed in greater detail in the next section.

c) Lasker's moist adiabatic models. Based on the first law of thermodynamics

$$dQ = dU + PdV + Ldn_a, \tag{3.59}$$

where the last term corresponds to the quantity of heat released during sublimation of a comparative quantity n_a moles of ammonia, Lasker derives the following equations

$$\frac{T}{P}\frac{dP}{dT} = \Big[\frac{P_d}{P}\frac{C_{pd}}{R} + \frac{P_a}{P}\frac{C_{pa}}{R} + \frac{n'_a}{n_a+n_d}\,\frac{C'_{Va}}{R} + \frac{P_a}{P}\frac{\Delta C'_p}{R} + \\ + \frac{P_a}{P_d}(\alpha+\alpha^2)\Big]\frac{1}{1+(1+\alpha)\frac{P_a}{P_d}} \tag{3.60}$$

where P_d is "dry" gas pressure; P_a is ammonia pressure; N'_a and C_{Va} are the /83
quantity and heat capacity of ammonia in the solid state;

$$\Delta C_p = G_{pa} - C'_{Va},$$
$$\alpha = \frac{T}{P_a}\frac{dP_a}{dT}. \tag{3.61}$$

Discarding in this equation the terms which are associated with the heating of solid ammonia, since even n_a is a low value, we obtain

$$\frac{T}{P}\frac{dP}{dT}=\frac{\frac{P_\mathrm{d}}{P}\frac{C_\mathrm{pd}}{R}+\frac{P_\mathrm{a}}{P}\frac{C_\mathrm{pa}}{R}+\frac{P_\mathrm{a}}{P_\mathrm{d}}(\alpha+\alpha^2)}{1+(1+\alpha)\frac{P_\mathrm{a}}{P_\mathrm{d}}} \tag{3.62}$$

The pressure of saturated vapors of ammonia are represented by the following temperature function

$$P_\mathrm{a}(T)=1{,}325\cdot 10^{13}e^{-\frac{3753.56}{T}} \tag{3.63}$$

(P is in dynes/cm^2, T is in °K). The concept of the sublimation level is introduced where NH_3 partial pressure equals the pressure of the sublimating saturated vapors:

$$n_\mathrm{a}P_s=P_\mathrm{a}(T_s) \tag{3.64}$$

(P_s and T_s are total pressure and temperature at the sublimation level). Below this level the NH_3 partial pressure is less than the pressure of the sublimating vapors.

The number of molecules of a given gas above a unit area of the sublimation level equals

$$\eta_i=\frac{1}{g\mu m_\mathrm{H}}\int_0^{P_s}\frac{P_i}{P}\,dP, \tag{3.65}$$

where m_H is the mass of the hydrogen atom. For non-condensing components:

$$\eta_i=\frac{n_iP_s}{g\mu m_\mathrm{H}}, \tag{3.66}$$

and for saturated ammonia

$$\eta_\mathrm{a}=\frac{1}{g\mu m_\mathrm{H}}\int_0^{T_s}\frac{P_\mathrm{a}(T)}{P}\frac{dP}{dT}\frac{\xi_\mathrm{a}}{g\mu m_\mathrm{H}}, \tag{3.67}$$

where ξ_a represents the effective ammonia pressure.

With the aid of an electronic digital computer Lasker calculated pressures P_s and ξ_a, and then calculated relative pressure and temperature values at various altitudes above the sublimation level for all combinations of the /84
following values of basic quantities T_s and n_a: T_s = 150, 160, 170, 180°K; n_a = 0.00316; 0.01; 0.0316; 0.1 and for three versions of the qualitative

composition of the atmosphere: hydrogen only, hydrogen and helium in various quantities, and helium only.

Figure 25 shows the results of calculations for a mixture containing equal quantities of hydrogen and helium. These results are shown in the form of lines of equal values (isolines) of log P_s and log ξ_a in a log n_a and T_s coordinate system. Through the use of this graph it is possible to find sublimation temperature T_s if the quantities of hydrogen and ammonia above this level determined from observation are given. If $\eta_a = 7 \cdot 10^2 \cdot 2{,}867 \cdot 10^{19}$ molecules/cm^2, then log $\xi \simeq 2.4$. Pressure P_s is determined from (3.66) if the quantity of hydrogen in cm-atm and the relative number n_i of molecules are known.

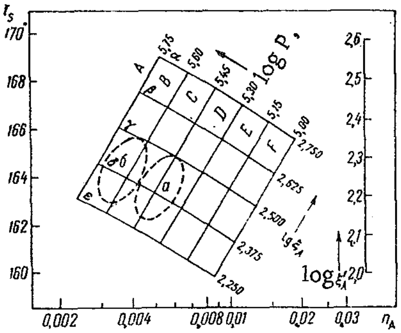


Figure 25. Temperature and Pressure Calculations in the Moist Adiabatic Atmosphere of Jupiter (After Lasker).

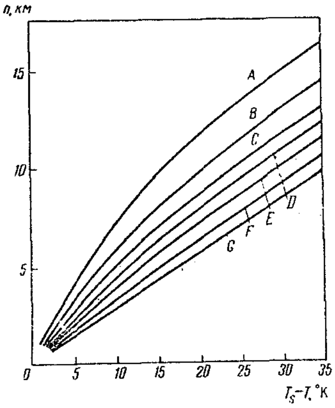


Figure 26. Temperature Dependence on Altitude Above the Sublimation Level (After Lasker).

Having accepted $\bar{\mu} = 3.3$ and the equivalent thickness of the hydrogen layer as 5.5 or 8.5 km-atm (the latter value corresponds approximately to saturation lines in the H_2 absorption band), Lasker found, correspondingly: a) $T_s = 163.6$°K, $n_a = 0.0052$: b) $T_s = 164.2$°K; $n_a = 0.0037$. In Figure 25 these data correspond to points A and B, the dashed contours around which designate the possible limits of deviation in values due to errors in log ξ_a and log P_s of approximately ±0.1.

Temperature dependence on altitude above sublimation level h is shown in Figure 26, where /85

$$z = \frac{g\bar{\mu}}{R} h. \qquad (3.68)$$

Curves A-G correspond to the various given values n_a = 0.015; 0.010; 0.007; 0.005; 0.003; 0.001; 0.000 where T = 160°K. From the right side on the axis of the ordinate h values are noted where $\bar{\mu} = 3.3$. It is not difficult to determine from this graph the value of the vertical temperature gradient. Curve G (n_a = = 0) represents a temperature change when ammonia condensation is not present, i.e., its slope corresponds to the dry adiabatic temperature gradient. Where $n_a = 0.015$ up to altitude ~ 10 km, the temperature gradient is approximately two times smaller than the dry adiabatic gradient, but at altitudes $h > 10$ km ammonia condensation no longer plays any significant role and the gradient becomes equal to the dry adiabatic. Where $n_a \simeq 0.005$ (curve D) the difference between the "moist" and "dry" temperature gradients is still comparatively large but since the relative quantity of ammonia is apparently still less than the curves beginning with E will be closer to real conditions in the Jovian atmosphere. Let us assume that hydrogen and helium are contained in the Jovian atmosphere in equal quantities. If we assume the hydrogen quantity to equal 27 km-atm (this is probably the maximum upper limit), then where $n_H = 0.5$ we find that $P_s = 1.94 \cdot 10^6$ dyne/cm^2 or $\log P_s = 6.288$. In extrapolating this curve from $\log \xi_a \simeq 2.4$ to this value $\log P_s$, we obtain $T_s \simeq$ $\simeq 166$°K and $n_a \simeq 0.001$. This value for T_s almost coincides with the corresponding value $\log \xi'_a = 2.4$ in an atmosphere not saturated with ammonia (in Figure 25 this is the vertical scale $\log \xi'_a$ in the right side of the drawing). The value $n_a = 0.001$ in Figure 26 corresponds to curve F which at an altitude of $h = 5$ km is already practically parallel to curve G and at lesser altitudes the slope differs very slightly from this curve. Thus according to Lasker's calculations as well, with a relative NH_3 quantity < 0.001 the difference between the "wet" and "dry" temperature gradients are totally unimportant.

Assuming that the hydrogen and helium content in the Jovian atmosphere to be equal, Lasker calculated the vertical pressure gradient above the sublimation level as a function of temperature difference $T_s - T$. For pressure he introduces the relative value P/P_s, the behavior of which is shown in Figure 27, where curves A, C and E correspond to $T_s = 160$°K and $n_a =$ $= 0.01$; 0.00316 and 0, and curves B, D and F correspond to $T_s = 170$°K with the same values for n_a. It can be seen from the graphs that a temperature difference in the sublimation level of 10° is not reflected significantly in pressure change with altitude, whereas the presence in the atmosphere of 1% of condensed ammonia changes the pressure gradient appreciably. At altitudes greater than 10 km pressure behavior is practically identical in all cases /86
but value $P(T)$ at the same temperature may diverge (depending on n_a by approximately 10%.

In Lasker's models the behavior of the atmosphere of Jupiter is not completely clear below the sublimation level, with a depth at which formation of cloud layers are still possible. The extent of the ammonia cloud layer with respect to altitude remains ill-defined. Lasker derives only corrections for the temperature of the sublimation level which allow for altitude above the level which reflects the radiation of the cloud surface (Δh). Thus for $n_a = 0.005$, $\Delta T_s = 2.3\ \Delta h$° K/km. Apparently the maximum thickness must be of the order of 10 km.

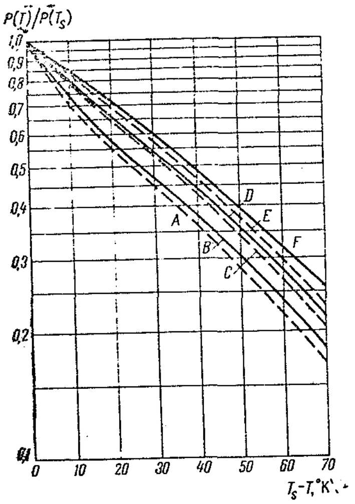


Figure 27. Relative Pressure Behavior as a Function of Temperature in a Moist Atmosphere (After Lasker).

Calculations for models of the atmospheres of the giant planets were published recently, accomplished by L. Trafton [213] with consideration for atmospheric opacity to thermal infrared radiation caused by the induced pressure of hydrogen dipole absorption. Trafton computed four models for Jupiter, based on different ratios between the H_2 and He content (either 1:0, or 1:1) and with a Jovian equilibrium temperature of 121°K. The basic results of these calculations are shown in Table 3.5.

We see that in general these models do not differ fundamentally from those examined above. The pressure at the surface of the cloud layer is $P_0 \simeq 1$ atm.

d) Temperature and pressure in the interior of the atmospheric layers. In view of existing uncertainties in our concepts /87 concerning temperature and pressure distribution in the outer atmosphere and in the cloud layer of Jupiter, it is difficult, based only on theoretical considerations, to place confidence in the possibility of compiling a sufficiently reliable prediction of the temperature-barometric conditions in atmospheric layers which are situated near the planetary cloud cover. Nevertheless such numerical calculations were made by R. Halle, who reported his results at a conference on the physics of Jupiter in the U.S.A. in 1962. We can only judge this work by a short report on the conference [101].

TABLE 3.5. JOVIAN ATMOSPHERIC MODELS AFTER TRAFTON

Parameter	I	II	III	IV
He/H_2	0	0	1	0
NH_3/H_2	0,0002	0,0002	0,0002	0,0002
CH_4/H_2	0,003	0,003	0,003	0,003
Effective temp.,°K	130	120	120	110
Temp. of the isothermal stratosphere, °K	100,5	93,6	95,5	85,3
Temp. at the upper limit of the convection zone, °K	149	139	158	131
H_2 content above the cloud layer, km-atm	28	30	38	32
Temp. gradient in the convection zone, °K/km	2,1	2,4	3,3	3,1

Tr. Note--commas indicate decimal points.

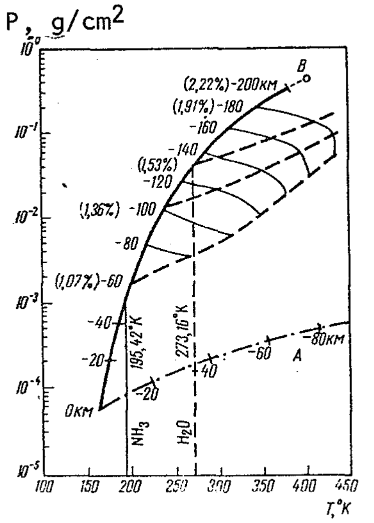


Figure 28. Density Change with Depth and Temperature Below the Limit of the Cloud Layer of Jupiter (After Halle).

Considering the thermodynamic role of the processes of ammonia condensation, and in the interior of the layers presumably of water vapor as well, Halle came to the conclusion, which is completely understandable to us, that the temperature gradient increase with depth is considerably lower than that which is obtained without consideration for phase transitions of condensed atmospheric components. Figure 28 shows the results of a calculation of the dependence of Jovian atmospheric density on temperature under various conditions below the limit of the cloud layer. Curve A corresponds to a dry adiabatic atmosphere. A very rapid increase in temperature with depth and with a comparatively small increase in density must occur in a dry adiabatic atmosphere. The numbers along the curve designate depth from the upper cloud limit. At a depth of 80 km the temperature reaches a value of 425°K (152°C). However when the product of condensation and sublimation of ammonia are present in the atmosphere the behavior of density with temperature and depth will follow the moist adiabat (curve B). Here the temperature increases with depth more slowly but nevertheless the pressure increase rapidly in the interior of the /88 atmosphere. In agreement with curve B at a depth of 80 km, the temperature climbs only to 220°K, but density increases by approximately 100 times. At a depth of more than several dozens of kilometers the density-temperature curve may act differently depending on the relative ammonia content. Below the saturation level of ammonia the moist adiabat is transformed into a dry one, so that the change in density follows one of the dashed curves, almost parallel to curve A. Beginning at a certain depth within the atmosphere, conditions may develop which are favorable for the condensation of water vapor. There the adiabat again will be "moist" to the depth where water vapor also becomes unsaturated.

It is possible to estimate the thickness of the ammonia cloud layer from these calculations. With a relative ammonia content of approximately 1% the thickness obtained is approximately 50 km. However for the present it is apparently impossible to arrive at an exact result since the moist adiabatic temperature and as a result the slope of curve $\rho(T)$ will change, depending on the relative quantity of NH_3. Therefore the real (or close to the real) relationship $\rho(T)$ may fall within the range between curves A and B, or, on the other hand, become steeper than curve P, which is less probable, since an excessively high relative concentration of ammonia would be required.

Halle comes to the conclusion that even at a depth of several hundred kilometers matter in the Jovian atmosphere may be transformed into a solid state under the influence of the very high pressure of the superimposed gas layers.

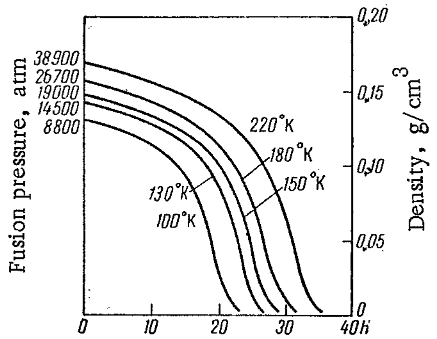


Figure 29. Density Change in an Isothermal Hydrogen Atmosphere with Altitude Above the Solid Surface of Jupiter (After De Marcus).

Interesting results were obtained by De Marcus who published calculations for isothermal models of hydrogen atmospheres in a number of his works [69, 72]. He employed experimentally obtained correlations between the volume, pressure and temperature of molecular hydrogen, extrapolating these to values of pressure corresponding to the fusion of solid hydrogen. Numerically integrating at a fixed temperature the hydrostatic equilibrium equation $dP/ = -\rho g$, De Marcus in the final analysis /89
obtained density change curves of the atmosphere with altitude above the surface of solid hydrogen. These curves, calculated for isothermal atmospheres with various temperatures, are shown in Figure 29. The abscissa is marked with values of relative altitude in units of scale height (altitude of a homogeneous atmosphere). Attention is directed to the fact that near the solid surface of Jupiter the density of an atmosphere of molecular hydrogen falls very slowly with altitude, remains almost constant up to an altitude of 15-20 H, and it is only at greater altitudes that it begins to fall very sharply. The region of an atmosphere with an almost constant density ($0.1 < \rho < 0.2$) in accordance with its properties, i.e., density and viscosity, shows a great deal of resemblance, in the opinion of De Marcus, to a liquid; he applies the term "ocean" to this atmospheric zone. Where T = 150°K the depth of such a homogeneous "ocean" equals approximately 240 km and the pressure on the solid surface is about 27,000 atm. The total thickness of the atmosphere obtained in this connection is about 800-1,000 km.

These models of hydrogen atmospheres which to a certain extent illustrate the conditions in which matter may be found in the depth of the Jovian atmospheric layers of course represent only certain approximations to real phenomena which occur on Jupiter. First of all the internal atmospheric layers are apparently very far removed from isothermy, and all the more so if Jupiter is characterized by the release of internal heat which must impart a convective nature to the thermal conditions in the atmosphere. It should not be forgotten that the Jovian atmosphere does not consist of pure hydrogen. Therefore it is necessary to develop models which take maximum cognizance of data concerning the chemical composition and temperature of the atmosphere.

CHAPTER 4. /90

THE CLOUD COVER OF JUPITER

§1. The Structure of the Visible Surface of the Cloud Layer

a) The classification of cloud zones and bands. Notwithstanding the rapid variability of details on the visible surface of Jupiter, the basic formations--dark and bright belts, in motion in parallel to the equator--are subject to comparatively simple classification and nomenclature. First of all it was accepted to call the dark sections of the cloud cover belts and to call the bright regions, situated between the belts, zones. It should be noted however that sometimes due to a great amount of difference in the color of individual cloud belts on photographs under different rays, the same belt may seem to be both dark and bright.

The basic, most intensive and the broadest belts are situated near the equator, at altitudes of approximately 4 to 20° on both sides of the equator (Figure 30). These belts are called the South and North equatorial or tropical belts since during different years they have been situated either in the tropical planetary belt or have approached so closely that they have merged, completely covering the ordinarily bright equatorial zone, as occurred, for example, in 1962-1963. In English literature these belts are called the North and South equatorial belts and are abbreviated NEB and SEB. In the bright equatorial zone (EZ) sometimes a fine dark belt (EB) is observed. The South equatorial belt (SEB) often consist of two parallel or almost parallel components. Sometimes the NEB is divided into two components.

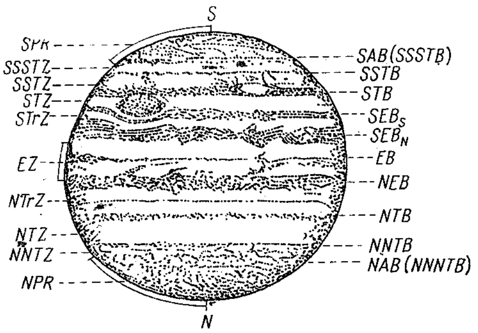


Figure 30. Basic Cloud Zones and Belts on the Jovian Disk.

In the temperate latitude region are situated the North and South temperate belts (NTB and STB), each of which may consist of two or more components abbreviated as NTB, NNTB, NNNTB, STB, SSTB and SSSTB, respectively. Finally, beginning at an approximate latitude of 45° and extending to the poles are the greyish polar regions (NPR and SPR), which are usually devoid of a pronounced structure. Sometimes fine "arctic" belts (NAB and SAB) are visible near the edges of the polar regions which face the equator.

The latitude of the borders and the width of the belts change from year to year by several degrees. Below are listed the limits of the fluctuations in the latitudes of the basic bands, compiled according to a survey of micrometer measurements of belt latitudes from 1908 to 1947, completed by the British Astronomical Association. The changes in latitude may reach 10°: /91

Belt	Limits of Measurements (in degrees of latitude)	
	From	to
Southern edge of the N-polar region	+40,0	+50,2
NN temperate belt	+33,1	+38,9
N temperate belt	+24,5	+32,2
Northern edge of the equatorial belt	+12,7	+22,0
Southern edge of the N equatorial belt	+4,5	+9,0
Northern edge of the S equatorial belt	—4,4	—9,0
Southern edge of the S equatorial belt	—16,4	—21,8
S temperate belt	—26,7	—30,5
SS temperate belt	—37,0	—45,4
Northern edge of the S polar region	—57,4*	

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*One measurement
Note--commas indicate decimal points.

The minimum latitude values indicates above for the edges of the North and South equatorial bands facing the equator pertain to the period of observations for which data has been compiled. The years when both belts merged at the equator (1881-1883, 1962-1963) do not fall within this period.

The width of the belt may be different at different jovigraphic longitudes. /92 These differences are particularly noticeable in the temperate belts. The borders of the belts are sometimes sharply defined and sometimes blurred and uneven. In wide belts a clearly vortical structure is noticeable which indicates a continuous turbulent motion within the cloud masses.

b) The basic characteristics of cloud formations. The North polar region has an average latitude on the southern border of approximately +48°. Separate belts are often visible near the southern edge. Sometimes, for example in 1924, matter of the NPR occupied the entire expanse down to the NTB, whereas in 1939-1940 it was possible to detect a division of the NPR into belts to a latitude of 60°. Sometimes in the NPR appear individual dark and more rarely bright patches. The bright zones between the NPR and components of the NTB usually contain no details. The dark NNTB is often fragmented, i.e., it consists of individual broken parts. Sometimes it seems to be a dual belt. A rapidly rotating spot was observed in 1941 and 1942 near its southern edge--it was displaced in longitude by 40° for more than one month.

The North temperate zone (NTZ) changes considerable from year to year both in width as well as in brightness. Sometimes it appears as the brightest region on the Jovian disk. Its width mainly depends on the dimensions of the temperate belt (NTB). Intensive disturbances have been observed at several longitudes in the NTB. In 1904 this belt suddenly disappeared and remained completely unnoticed until 1914. In 1924, on the other hand, it was very wide, occupying approximately 9° in latitude. In 1880 dark spots appeared near the edge of the NTB with a very short rotational period, amounting to approximately 9^h48^m. The disturbed region which contains the spots initially occupied approximately 40° in longitude but in one month it was extended over more than 120°. The next flare-up in activity in this region occurred in 1891, and again in 1929-1930 when disturbances on the southern edge of the NTB in the form of dark spots with a short rotational period (9^h49^m) occupied approximately 240° in longitude. The active region made a complete revolution around the planet with respect to the longitudinal system in the temperate latitudes in 38 days. Active processes in the NTB were also observed in 1939.

The Jovian regions in the tropical and in the equatorial belts of the planet are the most active and are subject to the most rapid and intensive changes. In the southern part of the north tropical zone (NTrZ) both dark spots and connecting bridges are observed, which are concentrated in particular toward the northern border of the NEB. The brightness of this zone changes not only with time but is also different at different longitudes. At times, for example in 1909-1910, at the beginning of 1911, in 1920-1921, and in 1939-1940 this zone was the brightest region on the Jovian disk. The most vigorous processes are observed at the southern side of the NEB, which faces the equator. Activity on the northern side of the NEB is less constant; in this /93 area a tendency to extend in parallel to the equator is a characteristic tendency of the dark details, which is apparently associated with the rapid rotation of Jupiter. Dark protuberances are frequently observed on the southern edge of the NEB with bright spots situated between them.

The equatorial zone (EZ) occupies on the average approximately 1/8 of the visible surface of Jupiter. Ordinarily it is bright and it is rarely situated in perfect symmetry with respect to the equator. Its width and boundary latitudes depend on changes which occur in the equatorial belts. The greatest width of the EZ may reach 18°. In this zone sometimes a fine band is visible which runs approximately along the equator. It is more often fragmentary, but it has sometimes attained an unusual intensity. Thus in 1937 several observers even considered the band to be a component of the SEB or NEB, since its width was unusually great. In 1939-1940 it was also broad and was even noted as a double band.

S. K. Vsekhsvyatskiy [103] expressed the original proposal that this equatorial band represents a shadow reflected on the EZ by a belt of comet-meteoric bodies, surrounding Jupiter similar to the ring at Saturn at a distance of 0.3-0.6 to 1 radius from the planetary surface. Although the possibility of the existence of such a ring around Jupiter is not excluded, observational data as shown in [104] does not serve to confirm this hypothesis. A belt is often linked by connecting bridges with other formations on the Jovian surface, breaks are observed in them, so that apparently this is all a detail of the cloud surface of the planet.

The brightness of the equatorial zone during various years changes quite intensively although in spite of this it still remains the brightest zone.

The South equatorial belt was the most outstanding in intensity at the very end of the last and at the beginning of the present century (from 1892 to 1908). After 1908 it was significantly less dark than the NEB, and only in 1912 did it again become the most pronounced belt on the Jovian disk. Total activity in the SEB is apparently less than in the NEB since sharp details in the form of spots, from which we may determine the period of rotation of the belt, appear less frequently here. But in return flare-ups in activity have occurred from time to time in the SEB which are much greater than in the NEB. These corresponded to periods when the southern component of the SEB disappeared or was greatly attenuated. This occurred in 1919-1920, 1928-1929 and in 1942-1943. The last great flare-ups in activity were observed in 1949 and in 1952-1953. The width of the entire SEB, which consists of two components, is usually somewhat larger than the NEB, with the exception of cases involving disappearance of the southern component. The latter represents one of the most interesting regions of Jupiter with respect to activity, together with the south tropical zone (STrZ). It is in this zone in particular that a /94 unique Jovian formation is observed--the Red Spot which has a practically fixed latitude of approximately 22°.5. The Red Spot gives rise to a disturbance of a specific type in the SEB in which a hollow forms at the point of contact with the spot; this hollow exists even when the spot itself is hardly noticeable or when it is not visible at all. In the southern component of the SEB individual spots with the longest rotational period and an extended period of the existence of details were observed.

A second remarkable object appears in the STrZ--the South Tropical Disturbance--which is an area of high activity, and which has a shorter rotational period than the Red Spot. As a result of this the conjunctions of the Disturbance and the Red Spot have been periodically observed, each time having attracted the attention of observers by unusual phenomena occurring during the interaction of the Spot with the Disturbance.

More than once the South temperate belt has become the second most pronounced belt on the Jovian disk. Between the STB and the SSTB lies the South temperate zone, ordinarily bright, but divided from time to time longitudinally by a fine band which sometimes passes through obliquely with respect to the zenographic parallel. The brightness is variable, due in particular to the appearance in the zone of irregular darkenings alternating with white spots.

Ordinarily two weak belts, the SSTB and the SSSTB are situated to the south of the STZ. The SSSTB represents an ephemeral formation which is not always visible. During certain years the region of the SSTB was rather seriously disturbed. Several times fine bright spots have been noted there.

The South polar region is ordinarily devoid of any kind of details, except for rare, fine bands. Darkening of the SPR often reaches the bands of the SSTB and even progresses to lower latitudes.

It is not possible here to give a detailed description of all phenomena and all changes which have been observed in the various zones of the Jovian disk. B. Peek's book [102], which has already been mentioned, is mainly devoted to such a detailed description. Therefore we shall turn mainly not to the morphological but to the physical aspects of the problem of the nature of the Jovian cloud cover.

§2. The Integral Optical Properties of Jupiter

a) The albedo and color. The magnitude of Jupiter in the V system during periods of the closest approach to the Earth amounts of $-2^{m}.6$; however even magnitudes now used reduced to the same distance from the sun and the earth during various years proved to be different, which reflects the change in intensity and relative area of the dark and bright cloud bands on the planetary /95 disk. Figure 31 shows long-term variations in Jovian magnitude observed in the period from 1860 to 1964, reduced to the photometric V system after D. Harris [105] and corrected for the distance from the sun and the earth (reduced to 1 AU). When there were no outstanding details on Jupiter (in 1951-1954) the absolute magnitude varied from $-9^{m}.48$ to $9^{m}.38$. In 1964 when the equatorial region of Jupiter was encompassed by a wide dark band the Jovian magnitude was V (1.0) = $-9^{m}.12$ according to the observations of A. F. Sharov and Ye. B. Kostyakova [106]. The reflective properties of Jupiter are apparently determined basically by properties of the cloud surface, at least in the range λλ 4000-6000 Å. Therefore the albedo and the color of Jupiter must characterize its cloud cover as a whole. According to Harris, the visual spherical albedo of Jupiter has a mean value of 0.73. This means that Jupiter reflects in all directions 73% of its incident light. The spherical albedo determined previously (Russell, Stumpf, Kuiper) resulted in values from 0.41 to 0.56. The fact is that in order to calculate the spherical albedo we must know the so-called phase integral q and the geometrical albedo p. The latter is determined directly from observations, and the phase integral for Jupiter may be calculated only on the basis if theoretical considerations, since observation of Jovian magnitude is possible only in a very narrow range of phase angle values--from 0 to 11°.6. Harris, utilizing known data concerning brightness distribution on the Jovian disk, accepted q = 1.65. But since limb darkening of Jupiter depends on wavelength and changes with the shift from dark bands to bright bands and since the albedo also depends on wavelength the exact value of the spherical albedo in different colors is so far /96 unknown.

The reflectivity of the Jovian cloud layer is reduced during the transition from visible rays to ultraviolet rays (Figure 32). In the near-infrared region of the spectrum the geometrical albedo of Jupiter is also reduced but in this case it is caused by the presence of intensive absorption bands of methane, especially at λλ 7250, 8860, and 9000 Å. The geometrical albedo for Jupiter was established at 0.26 at 2700 Å in the ultraviolet region with the aid of high-altitude measurement from the "Aerobee" rocket in 1957 [107]. Thus Jupiter is significantly "more yellow" than the sun. This is also indicated by spectrophotometric observations of which we should note the photoelectric measurement made by R. Younkin, G. Munch [108] and D. Taylor [75].

According to measurements by Younkin and Münch (Figure 33), the maximum energy distribution in the Jovian spectrum lies in the region λλ 5500-6100 Å. The sharp drop in intensity attracts attention in the region λλ 3850-4300 Å, after which for λ < 3500 Å the reflectivity curve becomes smoother. After reduction of the energy distribution observed to the solar spectrum, the maximum on the spectral reflectivity curve was displaced toward λ 6750 Å, but in the ultraviolet, the presence of a drop in the curve leaves no doubt.

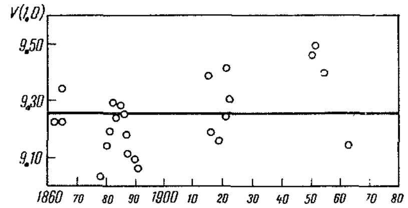


Figure 31. Variation in the Magnitude of Jupiter in the V System. The Absolute Magnitude of the Planet is Indicated, Reduced to a Zero Phase Angle and to a Distance from the Earth and the Sun of 1 AU (After Harris [105], A. Ye. Sharov and Ye. B. Kostyakova [106]). The heavy line is the average magnitude of Jupiter.

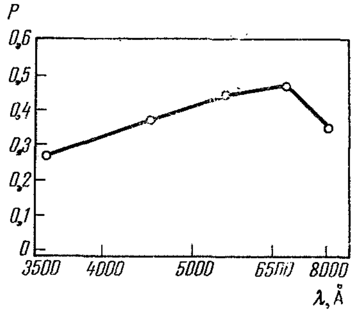


Figure 32. Dependence of the Geometric Albedo of Jupiter on Wavelength (After Harris).

In the far ultraviolet, according to spectral observations from rockets [25, 26] the geometrical albedo of Jupiter increases toward the short waves from 0.19 at λ 3000 Å to 0.38 at λ 2100 Å. The basic role here is probably played by reflection not from the surface of the Jovian cloud layer, but from the outer atmosphere which intensively scatters the ultraviolet radiation.

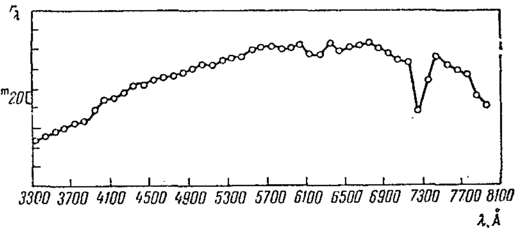


Figure 33. The Reflectivity r_λ of Jupiter Versus the Spectrum (After Younkin and Münch).

The color of celestial bodies is quantitatively characterized by the value of the color index. With photographic observations the normal color index equals the difference in stellar magnitudes of an object in spectrum intervals with effective wavelength of 4400 and 5500 Å. A small number of estimates of the normal color index of Jupiter exists. If we disregard the old estimates of Graff and Russell (CI = $0^{m}.50$ - $0^{m}.66$), then all of the remaining ones fall within the limits of ± $0^{m}.88$ to $+1^{m}.10$. In the U, B, V system the mean color index of Jupiter is B - V = $+0^{m}.83$.

There are no systematic data available concerning changes in the color index of Jupiter with time. There would hardly be any point in organizing such observations at the present time, since the volume of information obtained in /9 this connection would be insignificant. In fact, while registering only changes in the integral light of the planet with a far from uniform disk brightness, we do not know what to relate these changes to or what processes on the surface of the Jovian cloud layer caused the changes. The systematic photography of the Jovian disk in different light with appropriate standardization and the parallel determination of its integral brightness would therefore appear to be more advantageous.

b) Ultraviolet continuous absorption in the Jovian spectrum. As early as 1872 H. Vogel [109], while observing the visual spectrum of Jupiter, directed his attention to the fact that beginning at the end of the green region and especially in blue and violet rays the spectrum of Jupiter was attenuated in comparison with the spectrum of the sun and the sky. This phenomenon was subsequently forgotten and it was only in 1959 that Corliss and the Kiess again noted the presence on spectrograms of Jupiter of strong continuous absorption in the near ultraviolet [15], beginning from λ 4200 Å toward the short waves.

The spectrophotometric gradient G of Jupiter with respect to the moon

$$G = \frac{d \ln I_{♃}/I_{☽}}{d\lambda^{-1}} \qquad (4.1)$$

in the region λλ . 3700-4000 Å equals G_U = +7.38, according to their measurements. J. Heard [110] who also compared spectrums of Jupiter and the moon, came to a similar conclusion in 1959 concerning the increase in absorption in the Jovian spectrum on the short wave side. However H. Spinrad [111], having obtained several spectrograms of Jupiter and of the moon on April 28, 1961, /98 noted a lack of intensity reduction in the blue and ultraviolet portion of the Jovian spectrum in comparison to the moon. Therefore he considered the strong ultraviolet absorption, noted for Jupiter in 1959, to be an unusual event. In 1962 V. G. Teyfel' [112], on the basis of spectrophotometric comparisons of Jupiter and the moon, again detected the presence of intensive ultraviolet absorption. The curve of the relative intensity distribution along the Jovian spectrum (Figure 34) has a rather sharp bend near the wavelength λ 4200 Å. The relative spectrophotometric gradient obtained equaled, in the

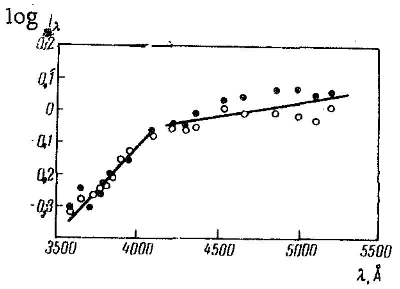


Figure 34. Ultraviolet Absorption in the Spectrum of Jupiter in Comparison with the Moon ($I_{\lambda} = I\lambda_{♃}/I\lambda_{☽}$). The black and white dots designate different periods of observation (see [112]).

short wave region shorter than 4200 Å, on September 13-14, 1962, G_U = 1.11--1.25; on October 11-12, 1962, G_U = 1.68-1.77; and in the region λλ 4200--5200 Å, G_B = 0.32-0.43. Thus in the ultraviolet the gradient is in fact significantly greater than in the visible region of the spectrum, although it does not achieve such a value as was obtained according to the observations of the Kiesses and Corliss. Similar observations were carried out by V. F. Kartashov in 1964 at the Observatory of the Astrophysics Institute of the Academy of Sciences of the Kazakh SSR. On August 28-29 he obtained in the interval λλ 3550-4200, Å G_U = 0.59 ± 0.07 and on August 30-31, G_U = 0.77 ± ± 0.10. These observations testify to the fact that ultraviolet absorption displays a variable nature. According to observations made by I.N. Glushneva [113] in 1963 with a slitless spectrograph, ultraviolet absorption is intensified up to λ 3500 Å, but with a further increase in wavelength it is attenuated (Figure 35).

Unfortunately all of the observations cited have a random nature, so that to speak of regularities in measurements of ultraviolet absorption is, for the present, premature. The single point that can be made on the basis of available observational data is that the ultraviolet absorption apparently displays a planetary nature. Spectrophotometric observations of individual /99 zones on the Jovian disk, accomplished by V. V. Avramchuk at the Main Astronomical Observatory of the Academy of Sciences of the Ukrainian SSR [181], by N. V. Priboyeva, Z. N. Grigor'yeva and by the author at the Astrophysics Institute of the Academy of Sciences of the Kazakh SSR revealed that dark and bright regions on Jupiter in the ultraviolet do not reveal substantial differences in absorption behavior in the spectrum, so that one cannot say that ultraviolet absorption is caused by the dark or bright matter of the planetary cloud cover.

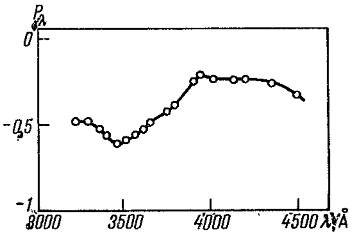


Figure 35. The Spectral Reflectivity (Geometrical Albedo) of Jupiter in the Ultraviolet (After I. N. Glushneva).

Kiess and Corliss attempted to explain ultraviolet absorption by the presence in the Jovian atmosphere of N_2O_4--a low-temperature polymer of nitrogen dioxide NO_2, for which there is in fact an absorption band in the ultraviolet. However the authors themselves indicate difficulties with this hypothesis, associated with the fact that in the presence of hydrogen and ammonia the quantity of this polymer decreases, as with other nitric oxides. In order to eliminate this difficulty the authors introduce a proposal concerning the stratification of N_2O_4 as a result of the gravitational separation of gases in the form of a certain layer in the outer atmosphere. It is more probable to suppose that ultraviolet absorption is a property of cloud layer particles or at least of a specific class of particles which are present in approximately identical quantity both in dark belts as well as in bright zones. In any case ultraviolet absorption in the Jovian spectrum still requires careful and systematic study.

c) The reflecting properties of Jupiter in infrared rays. The total reflectivity of Jupiter in infrared rays, if we examine only the continuous spectrum, changes insignificantly with wavelength in the region λλ 0.6-1.1 μ, but absorption bands of methane in this region (Figure 36) cause an intensive brightness minimum in the shape of the spectral curve. As shown by Figure 37 the arbitrarily drawn continuous spectrum line in this region appears in almost neutral fashion, i.e., the inherent reflectivity of the dispersed phase (of /100 aerosols) in the Jovian clouds remains almost constant.

Measurements at wavelengths greater than 1 μ are greatly hindered by the presence of powerful absorption bands of oxygen and water vapor of earth origin. Kuiper (see [105]) compared the relative brightness of the planet on wavelengths of 1 and 2 μ. The ratio of the intensities for Jupiter at these wave lengths was obtained as $I_2/I_1 = 0.21$, and if normalized in the same manner as the sun, then $I_2/I_1 = 1$. The low reflectivity of Jupiter in the range of approximately 2 μ is caused first of all by strong methane absorption. The CH_4 absorption bands are overlapped to such an extent that it is difficult to say anything definite concerning the reflectivity of cloud particles.

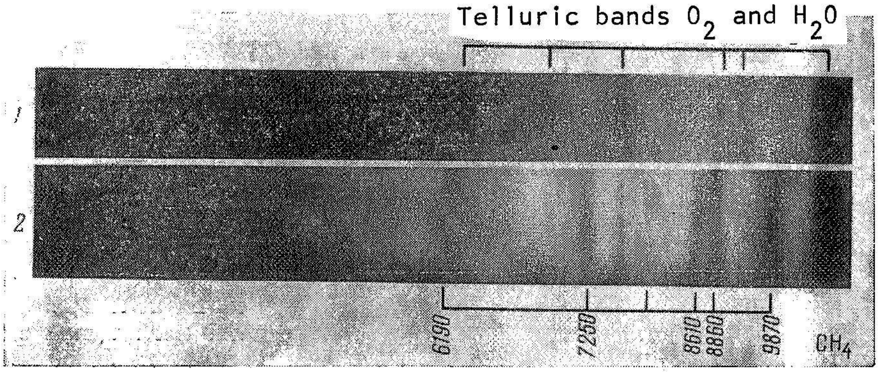


Figure 36. Spectrograms of the Moon (1) and Jupiter (2) in the Infrared Region, Obtained at the Astrophysics Institute of the Academy of Sciences of the Kazakh SSR with an EOP [Image Converter Tube].

Figure 38 shows a composite curve of the spectral reflectivity of Jupiter in a wide interval of wavelengths--from 0.2 to 3 μ. The ratio I_2/I_1 as easily defined, was found to equal 0.22, i.e., it practically coincides with the value found by Kuiper.

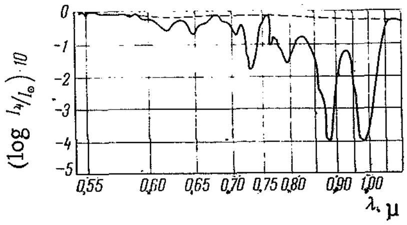


Figure 37. The Spectral Curve of Jupiter with Respect to the Sun in the Region λλ 0.55-1.1 μ, Obtained E From Photographs with an IOP [Image Converter Tube].

The reflectivity of the dark region on the Jovian disk in infrared light can be distinguished sharply from what occurs in the visible region of the spectrum. Thus, for example, in photographs obtained by the author in 1964 in infrared light (λ_{eff} = 8500 Å) with the aid of an image converter tube, Jupiter presented a completely opposite appearance than was observed in blue and green light; the dark belt in the equatorial region in infrared light was completely missing and the clearly visible areas included only the narrow northern part of the North equatorial belt and a narrow band in the South tropical belt of Jupiter, so that the Jovian appearance in infrared light in 1964 was reminiscent of its appearance in visible rays in 1957, when only several thin bands were visible on the disk.

§3. The Photometric Parameters of the Jovian Cloud Cover

a) The theoretical brightness distribution on a planetary disk, surrounded by an opaque atmosphere. Until the accomplishment of direct probing of the atmosphere, photometric and partially spectrophotometric observations presently serve as the basic source of information concerning the properties and nature of particles in the Jovian cloud layer. Depending on particle shape, dimensions, reflectivity and absorptivity, the cloud cover must react differently to changes in illumination conditions by a change in the apparent brightness of its individual segments. By comparing the observed brightness distribution on the planetary disk with the brightness calculated theoretically it is possible to establish which values fixed during calculation of atmospheric parameters are best satisfied by the results of observations. Unfortunately, especially for giant planets, in this connection it is not possible to hope for the acquisition of a uniform result from photometric observations alone. They must be examined only as part of the complex of optical and radiometric investigations and only those data must be selected which are not in contradiction to data obtained by other methods. /10

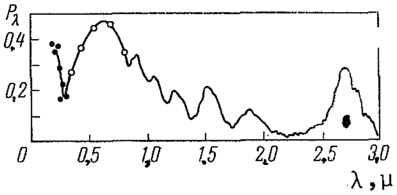


Figure 38. A Composite Curve of the Spectral Reflectivity of Jupiter (After Danielson) [74].

The atmosphere of Jupiter may be considered as practically opaque on all segments of the planetary disk. The cloud layer is extended in altitude for at least several kilometers, so that direct radiation from the sun does not reach deep layers of the atmosphere. Thus the optical thickness of the Jovian atmosphere must be very great. All brightness distribution calculations for the planetary disk therefore must be accomplished for $\tau = \infty$. We cannot exclude that several optical effects may be created in the outer atmosphere, the optical thickness of which is clearly less than 1 in the visible region of the spectrum, although up to the present time the value has not been exactly defined. In most cases we may accept $\tau_H = 0$ for theoretical calculations.

Brightness distribution on the planetary disk is construed to mean the dependence of intensity I reflected by individual segments of the planet on the angles of incidence and reflection (i and ε) or on their cosines ($\xi = \cos i$, $\eta = \cos \varepsilon$) and on the ϕ in the azimuths of incident and reflected radiation. As we shall see below this dependence proves to be rather complex in its analytical expression.

Brightness distribution on the planetary disk with $\tau = \infty$, or limb darkening, depends on several parameters which characterize the optical properties of the atmospheric components. The basic parameters which characterize the medium in which light scattering and absorption occur include the scattering factor, or the single scattering albedo $\omega = \sigma/(\sigma + \kappa)$, which we have already discussed in the first chapter, and the scattering indicatrix $x(\gamma)$ or $x(\cos\gamma)$, which is a function characterizing the probability of quantum scattering in various directions (at angles γ to the direction of incident radiation). In general form the scattering indicatrix may be written in the form of an expansion of Legendre polynomials

$$x(\gamma) = 1 + x_1 P_1(\cos\gamma) + x_2 P_2(\cos\gamma) + \dots \qquad (4.2)$$

Frequently in theoretical calculations either the spherical indicatrix $x(\gamma) = 1$ or a simplified presentation of the non-spherical indicatrix is employed, while retaining in (4.2) only the first two terms:

$$x(\cos\gamma) = 1 + x_1 \cos\gamma, \qquad (4.3)$$

where x_1 is a parameter which characterizes the degree of elongation (asymmetry) of the scattering indicatrix. It should be noted that with scattering on large particles, as shown by laboratory measurements in investigations of the optical properties of the Earth's atmosphere, a more extended and asymmetrical indicatrix is obtained which cannot be presented in such a simple form as in (4.3). /102

The formulas derived by V. A. Ambartsumyan [40] and V. V. Sobolev [41] are most convenient for brightness distribution calculations on the Jovian disk. We shall give the derivation here of these formulas, which the reader may find in the works referenced. We shall introduce only the final result--the formulas which are suitable for direct application in our calculations.

The intensity of radiation diffusely reflected from a segment of the planet in a given direction is associated with the intensity of incident solar radiation which falls upon the planet by the following relationship:

$$I(\eta,\ \xi,\ \varphi - \varphi_0) = S\xi\rho\,(\eta,\ \xi,\ \varphi - \varphi_0), \tag{4.4}$$

where S is the intensity of solar radiation which strikes a unit area of the planet, perpendicular to the solar rays; ρ is the brightness coefficient of a given segment of the planet, the position of which on the disk is determined by the values η and ϕ, and illumination by the values ξ and ϕ_0.

It is possible to obtain from observations in the case of absolute photometry brightness coefficients for segments and details of the visible planetary surface, and in the case of relative measurements, relative intensity behavior on the planetary disk. Therefore in theoretical calculations it is possible not to introduce into (4.4) the quantity S, but to arbitrarily accept it as equal to unity, and to calculate only the value of the product $\rho\xi$ or even $\log(\rho\xi)$, which is more convenient for a comparison of observational and theoretical curves.

With a spherical scattering indicatrix, the brightness coefficient is represented by the simple expression

$$\rho\,(\eta,\ \xi) = \frac{\omega}{4}\ \frac{\varphi\,(\eta)\ \varphi\,(\xi)}{\eta + \xi}\ . \tag{4.5}$$

where $\phi(\eta)$ and $\phi(\xi)$ are auxiliary functions introduced by V. A. Ambartsumyan, the values of which do not necessarily have to be considered, since prepared tables of these functions already exist. Calculation of brightness distribution on the disk for phase angle $\alpha = 0$ is quite simple (i.e., for observations near opposition, when $\eta = \xi$:

$$I\,(\eta) = \frac{\omega}{8}\,[\varphi\,(\eta)]^2, \tag{4.6}$$

Brightness distribution on the planetary disk for such a case was calculated in the work of V. A. Ambartsumyan [40].

In the case of the simplest non-spherical scattering indicatrix (4.3) /103
the brightness coefficient ρ is expressed by three auxiliary functions: $\phi_0^\circ(\eta)$, $\phi_1^\circ(\eta)$ and $\phi_\perp(\eta)$ (and the same for the ξ function):

$$\rho\,(\eta,\xi,\varphi - \varphi_0) = \frac{\omega}{4\,(\eta + \xi)}\,[\varphi_0^\circ(\eta)\,\varphi_0^\circ(\xi) - x_1\varphi_1^\circ(\eta)\,\varphi_1^\circ(\xi) + x_1\varphi_1'(\eta)\,\varphi_1'(\xi)\cos\,(\varphi - \varphi_0)]. \tag{4.7}$$

The auxiliary functions are determined by solving the appropriate integral equations which are not given here. Detailed tables of values of the auxiliary functions for various values of parameters ω and x_1 were calculated by I. N. Minin, A. G. Piliposyan and N. A. Shidlovskaya [44]. By using these tables it is possible to calculate the intensity distribution on the Jovian disk with different assumptions concerning the degree of elongation of the scattering indicatrix, for different true absorption in the cloud layer and at various phase angles. Several families of theoretical curves of intensity distribution along the planetary equator are shown as an example in Figure 39, calculated at the Astrophysics Institute of the Academy of Sciences of the Kazakh SSR with the aid of the tables mentioned above.

Consideration of an arbitrary scattering indicatrix significantly complicates calculations since in this connection it is necessary to introduce as many auxiliary functions as there are terms in the expansion of the scattering indicatrix based on Legendre polynomials. V. V. Sobolev derived an approximate formula for the brightness coefficient for an atmosphere of semi-infinite optical depth in the presence of true absorption, in which the /104 scattering indicatrix of the first order is arbitrary. For scattering of higher orders it is possible without loss, for the accuracy required for practical calculations, to accept the scattering indicatrix in an approximate form, i.e., (4.3). Then the brightness coefficient assumes the form

$$\rho(\eta, \xi, \varphi-\varphi_0) = \frac{\omega}{4}\frac{x(\gamma)}{\eta+\xi} + A(\eta, \xi) + A_1(\eta, \xi)\cos(\varphi-\varphi_0). \tag{4.8}$$

For A and A_1 we obtained the following rather cumbersome equations:

$$\begin{aligned} A(\eta, \xi) = {} & \frac{\omega^2}{4}\frac{1}{1+k\eta}\frac{1}{1+k\xi}\frac{1}{3-\omega x_1+2k}\frac{1}{\eta+\xi}\{2(3-\omega x_1)(\eta+\xi)+ \\ & +[3+(1-\omega)x_1][3+(1-\omega)x_1+2k]\eta\xi - \\ & -2kx_1\eta\xi-2kx_1(\eta^2+\xi^2)-2kx_1^2(1-\omega)\eta^2\xi^2 - \\ & -x_1^2\eta\xi(1+k\eta)(1+k\xi)\}; \end{aligned} \tag{4.9}$$

$$\begin{aligned} A_1(\eta, \xi) = {} & \frac{\omega^2}{4}x_1^2\frac{3\pi^2}{32}\frac{\sqrt{(1-\eta^2)(1-\xi^2)}}{(3+2k_1)(1+k_1\eta)(1+k_1\xi)} \times \\ & \times\left[2+(3+2k_1)\frac{\eta\xi}{\eta+\xi}\right], \end{aligned} \tag{4.10}$$

where

$$k = \sqrt{(3-\omega x_1)(1-\omega)}; \qquad k_1 = \sqrt{3\left(1-\frac{\pi^2}{32}\omega x_1\right)}. \tag{4.11}$$

If we examine an atmosphere with comparatively small true absorption ($\omega > 0.9$), then in (4.9) and (4.11) we may disregard values of the order of ($1 - \omega$) and remove the appropriate terms from these equations. Then we shall obtain the following formula for the brightness coefficient

$$\begin{aligned} \rho(\eta_1, \xi, \varphi-\varphi_0) = {} & \frac{\omega}{4}\frac{x(\gamma)}{\eta+\xi}+\frac{1}{2}+\frac{3+x_1}{4}\frac{\eta\xi}{\eta+\xi}-\frac{1}{4}\sqrt{\frac{1-\omega}{3-x_1}} \times \\ & \times(2+3\eta)(2+3\xi)+\frac{x_1^2}{2(3+2\sqrt{3-x_1})}\sqrt{(1-\eta^2)(1-\xi^2)}\cos(\varphi-\varphi_0). \end{aligned} \tag{4.12}$$

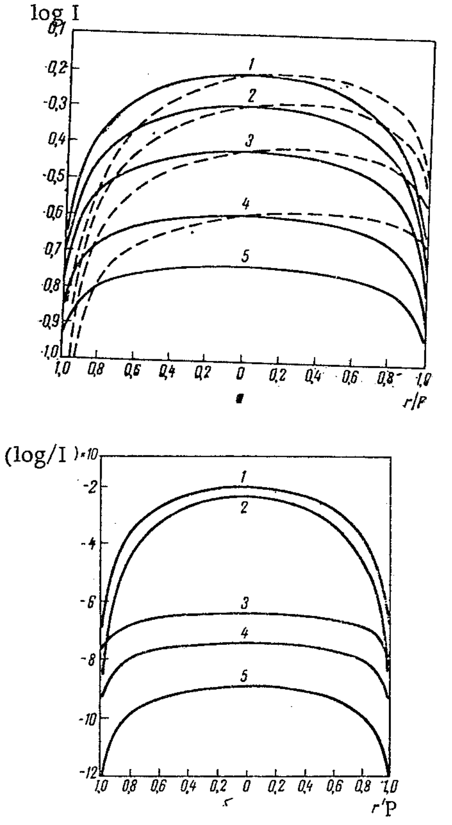


Figure 39. a) Brightness distribution on the planetary disk with a semi-infinite atmosphere where $x_1 = 0$ and at phase angles 0° (solid line) and 12° (broken line), for $\omega = 0.975$ (1), $\omega = 0.95$ (2); $\omega = 0.9$ (3); $\omega = 0.8$ (4) and $\omega = 0.7$ (5); b) Brightness distribution on the disk with $\omega = 0.975$ and $x_1 = 0$ (1) and +0.6 (2) and with $\omega = 0.7$ and $x_1 = -0.6$; 0; +0.6 (curves 3, 4 and 5 respectively).

In the first term of this formula we insert the value of the function x (γ), which corresponds to angle γ between the incident and reflected rays for a given point of the planetary disk. This formula must be applied with caution to observations concerning Jupiter, since in violet and ultraviolet light ω may be less than 0.9 in dark bands on Jupiter.

In comparing photometric observations of Jupiter with theory it is always necessary to remember that even good agreement between observational and theoretical curves still does not give us the right to accept unconditionally corresponding values for the parameters of atmosphere of this planet. A major shortcoming of earth-based photometric investigations of Jupiter, is the impossibility of observing Jupiter at phase angles greater than 12°, and as a result it is not possible to make measurements with confidence in the region of the terminator where effects could be detected which better reflect the atmospheric characteristics of Jupiter.

b) Results of photometry of the Jovian disk and their interpretation. Measurements of relative intensity distribution on the Jovian disk have been accomplished repeatedly, mainly by means of photographic photometry. A detailed survey of such investigations, accomplished in 1957, is contained in the work of V. N. Lebedinets [116]. The most systematic measurements were made in 1933 by I. Plaetschke in Wroclaw [117], by V. V. Sharanov at the Tashkent Observatory [115] and in particular by N. P. Barabashoa and his colleagues at the Kharkov Astronomical Observatory [118-122], where an extensive amount of material has been accumulated during photographic observations of Jupiter for a period of many years.

A shortcoming of a majority of the investigations was the excessively small scale of the image. Thus for Plaetschke the diameter of the Jovian disk on the negative was approximately 2.5 mm, for V. V. Sharanov the size was 0.8-3 mm, and on the Kharkov Observatory photographs, the diameter was 3.5 to 5.4 mm. The latter, therefore should have provided the most reliable results, especially since they encompassed a period of almost 30 years. Also available are the measurements of Kuiper (up to 1947) which were mentioned in the article by Van de Hulst [4]. In recent years regular photographic observations of Jupiter have been conducted at the Observatory of the Astrophysics Institute of the Academy of Sciences of the Kazakh SSR. The dimensions of /106 Jovian images obtained on photographs with 30 and 70 cm reflectors amounted to 7-13.5 mm.

The total brightness distribution on Jupiter is characterized by a pronounced darkening of the disk towards the limbs, which is observed both in bright zones as well as in dark belts. If we put isophotes on the Jovian disk by means of photometric measurement of the entire photographic image whereby utilizing the more rapid method of equidensitometry (a description of this interesting method may be found, for example, in [182]), it may be noted that a difference in isophote behavior for dark and bright bands occurs on the disk up to a distance of approximately 0.9 radius from the center of the disk. Near the edge of the disk this difference disappears and the isophotes acquire a circular shape while concentrically passing the contour of the edge of the disk (Figure 40).

Sometimes this effect of weakening of the contrast between the dark and bright details near the edge of the disk is explained by the influence of light scattering in the atmosphere above the clouds. But the real reason for the "disappearance" of dark belts near the limb is the different nature of the drop in brightness toward the limb; in dark belts, where true absorption is greater, limb darkening, as shown by theoretical calculations, must be less than in bright zones. This is illustrated in Figure 41: the ratio of intensities of the dark and bright bands $I(\omega_1)/I(\omega_2)$ approaches unity with proximity to the edge of the disk. In the polar regions of Jupiter divergence of isophotes is observed since the presence there of dark matter changes the nature of limb darkening in comparison with the equatorial zone.

If observations of Jupiter are conducted near opposition, when the phase angle $\alpha \approx 0$, intensity distribution along the equator must be symmetrical with respect to the central meridian and is satisfactorily presented by the following formula:

$$I(\eta) = I(1,0)[1 - q(1 - \eta)], \qquad (4.13)$$

where I (1.0) is intensity at the center of the disk; $\eta = \cos \varepsilon$; q is the so-called coefficient of limb darkening. This formula, although an approximation, satisfies observational data ordinarily where $0.4 < \eta < 1.0$, i.e., where relative distances from the center $r/R < 0.9$. This is in general completely sufficient for calculating q, although the behavior of the brightness distri- /107 bution curve near the edge of the disk does not present less interest. But with photographic photometry the edge segments of the image carry less useful information since photometric errors associated with the effects of photography, with atmospheric turbulence and other distorting factors is sharply increased near the edges where a sharp drop in the density of the negative occurs.

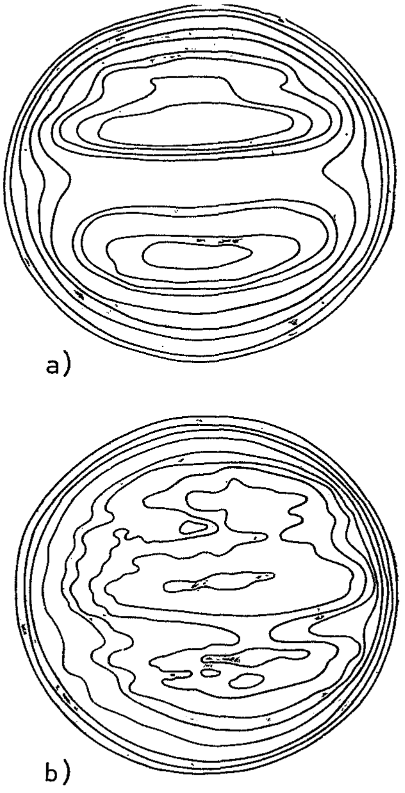


Figure 40. Isophotes on the Jovian Disk, Plotted by the Equidensitometric Method From Photographs in Blue Light, Obtained in 1962 (a) and in 1967 (b).

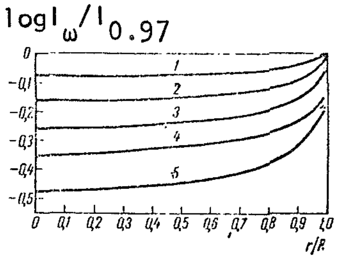


Figure 41. The Decrease in Contrast Between Dark and Bright Formations on Jupiter as the Limb of the Disk is Approached. The curves show the behavior along the disk of the logarithms of intensities $I(\omega)$ and I ($\omega = 0.97$) for $\omega = 0.94$ (1), 0.91 (2), 0.86 (3), 0.81 (4) and 0.73 (5).

In many cases a still simpler limb darkening characteristic is employed which does not require measurement at many points on the disk:

$$\beta = \frac{2I(0,5)}{I(1,0)}. \qquad (4.14)$$

This is a doubled ratio of intensities at distance $r/R = 0.866$, which corresponds to $\eta = 0.5$ or $\varepsilon = 60°$, and at the center of the disk ($\eta = 1.0$). The value β with a fixed scattering indicatrix increases with a decrease in ω, i.e., with an increase in true absorption in the atmosphere limb darkening becomes less sharply expressed and with fixed value ω and a non-spherical scattering indicatrix, value β increases during the transition from the indicatrix which is extended foreward ($x_1 > 0$), to the indicatrix which is extended to backward ($x_1 < 0$).

The total behavior of the curves representing limb darkening on Jupiter suggests the conventional Lambert law, in agreement with which a decrease toward the limb of the intensity of radiation reflected from an ideal matte surface is proportional to the cosine of the angle of incidence. The surface of the cloud layer, of course, does not resemble an ideal matte surface, and in addition, not only light scattering but also true light absorption occurs in the cloud layer. Therefore there are no fundamental bases for anticipating complete agreement between intensity distribution on the Jovian disk and the Lambert law.

In fact the curves observed do not satisfy the Lambert law, while divergence increases with the transition from red light to blue light.

According to early measurements by N. P. Baravashova and B. Ye. Semeykin [120,121] and V. V. Sharanov [115] in red light, $\beta = 0.8$, but with the transition to the short-wave region of the spectrum, value β increases to the extent that in blue rays $\beta \simeq 1.2$. Kuiper's measurements resulted in the same effect [4]: at λ 3500 Å $\beta \approx 1.52$, but in the infrared region ($\lambda\lambda$ 1.3-1.6 μ) $\beta < 1$. According to our measurements in 1964, accomplished with photographs and spectrograms of Jupiter obtained with the aid of an image converter tube on the 70-cm reflector of the Astrophysics Institute of the Academy of Sciences of the Kazakh SSR, β fluctuates from 0.6 to 1.0 in the region $\lambda\lambda$ 0.7-0.9 μ. On photographs of Jupiter with a scale of 4" in 1 mm, obtained in 1964 and 1965, the β values were different, as follows: in infrared light (0.8 μ) 0.60-0.75, in red light the value obtained was 0.90, in yellow light, 0.98 and in blue light 1.15-1.20. Thus all measurements reveal that with the transition from infrared to ultraviolet rays, relative limb darkening increases. /108

This effect sometimes is attributed to the action of the outer atmosphere in which light scattering increases with a decrease in wavelength and develops additional brightness near the limbs of the disk in the short-wave region of the spectrum. A rule of the outer atmosphere in the photometric properties of Jupiter has still not been completely studied but for the present there is no necessity for including it in explanations for limb darkening of the Jovian limb in various rays. The effects observed in the visible range of the spectrum are explained to a sufficient degree by applying the usual theory of light scattering and absorption in a semi-infinite atmosphere, i.e., in the cloud layer of Jupiter. Theory revealed that with an increase in true absorption limb darkening must decrease simultaneously with an increase in the albedo of the cloud surface. The coloring of the Jovian cloud layer as a whole, as we have already seen, is yellowish, so that true absorption in the cloud particles increases in the short-wave direction. Qualitatively observed limb darkening on Jupiter is completely explained by the reflecting properties of its cloud cover.

We have already noted that it is not possible to obtain unique parameters of the optical properties of the Jovian atmosphere from direct comparison of observational and theoretical curves. First of all it is almost never possible to obtain complete agreement of these curves. They may agree well in the range $r/R < 0.6$, but will diverge noticeably near the edge zone, or vice versa. The reason for this, on the one hand, lies in all kinds of photographic and photometric errors which develop near the limbs of the disk and, on the other hand, the real brightness distribution on the Jovian disk is not at all required to coincide with the theoretical distribution. Any theoretical calculations are based on more or less simplified initial conditions and propositions. The latter especially pertain to the scattering indicatrix or the phase function $\omega f(\alpha)$, established in theoretical calculations. Therefore photometric observations, strictly speaking, even with the most exact measurements and with the most careful consideration for errors may give us only certain probable limits for the values of parameters which characterize optical properties of the Jovian atmosphere.

At the present time we have available only quite rough estimates of the optical properties for Jupiter. According to V. N. Lebedinets [116], $\omega = 0.985\text{-}0.995$ where $x_1 = 0.9$. Yu. V. Aleksandrov [123] obtained for the bright zones of Jupiter $\omega = 0.987 \pm 0.003$ and $x_1 = 1.35 \pm 0.08$, and for the dark belts $\omega = 0.980 \pm 0.004$ and $x_1 = 1.29 \pm 0.10$ in the long-wave portion of the spectrum (red light). In blue light for bright zones $\omega = 0.982\text{-}0.990$ and $x_1 = 1.3\text{-}1.5$, whereas for dark belts $\omega = 0.974\text{-}0.984$ and $x_1 = 1.2\text{-}1.5$. It is true that these values were obtained under the assumption that the cloud layer of Jupiter is optically neutral, i.e., gray, and that the color effects /10 are caused by the outer atmosphere with optical thickness $\tau_H = 0.10\text{-}0.20$. Otherwise, as Yu. V. Aleksandrov believes, it is impossible to reconcile the brightness distribution observed on the Jovian disk with the theoretical distribution. Such a result cannot but cause doubts, since both photographic and spectral observations as well as color photographs of Jupiter indicate the fact that the diverse coloration observed on Jupiter is a property of the cloud formations themselves. Photometric observations of Jupiter, accomplished at Alma-Ata, lead to the conclusion that in red light in fact $\omega \geqslant 0.975$, but in blue light the value ω is reduced to 0.9 and below. Thus in 1962 the dark equatorial belt had a value in violet light $\omega = 0.70$; in blue light the value was 0.80, and in green and red light, approximately 0.97. The relationship between reflectivity and value ω for the dark belt was exactly the same as that obtained from theoretical calculations: the albedo of the band decreased toward the short-waves and limb darkening correspondingly decreased. The overlapping of light scattering and absorption in the outer atmosphere on neutral light reflection from the cloud layer did not give such an effect.

Therefore in our view it is more logical to interpret the observed photometric properties of the various sections of the Jovian disk mainly as properties of the cloud cover itself, as property of the particles which form it. Of course it is impossible to deny, without special organized investigations, a certain role for the outer atmosphere, but this role must not be considered a fundamental one in the optics of the Jovian atmosphere; for this purpose it would be necessary to ascribe to it exceedingly unusual properties, for example, the presence in it of intensive true absorption in a wide range of wave lengths.

§4. The Structure and Optical Characteristics of Individual Cloud Belts

a) Zones and bands. There is available a total of three works devoted to absolute photometry of the individual zones of Jupiter. These are works by L. N. Radlova [114] (1935), V. V. Sharonov [115] (1938) and V. N. Lebedinets [116] (1953-1954). Apparently the most reliable data is obtained from the latter work, which pertains to the reflectivity of the central portion of the bright equatorial zone of Jupiter. These data are shown in Table 4.1.

TABLE 4.1. THE REFLECTIVITY r_{br} OF THE BRIGHT EQUATORIAL ZONE OF JUPITER IN 1953 (AFTER V. N. LEBEDINETS)

Light Filter	Transmission Band Å	λ_{eff},Å	r_{br}	Light Filter	Transmission Band Å	λ_{eff},Å	r_{br}
Red	6300—6600	6480	0,849	Green	4820—5540	5210	0,673
Yellow	5220—6540	5940	0,758	Blue	4000—4600	4320	0,484

Tr. Note--commas indicate decimal points.

It is apparent from the Table that the reflectivity of bright zones of the cloud cover in blue light is almost two times less than in red light. Measurements of the contrast between the dark and bright bands on the Jovian disk, accomplished over a number of years by V. N. Lebedinets, revealed that contrast /110 increases with the transition from red light to blue light, i.e., the bands in blue light appeared to be much darker than in the red light. In 1933 the brightness ratio I_{da}/I_{br} in blue light approached 0.74, whereas in red light it amounted to 0.83-0.91. The maximum contrast for the current century was apparently observed in 1962, when according to the authors observation the relative brightness of the dark band, which occupied the entire equatorial region of Jupiter, in violet light equaled 0.50 and in blue light, 0.60. In green light the brightness amounted to 0.73 and in red light 0.85. If we transform these values into brightness coefficients, accepting Table 4.1 as initial data for the "bright" substance we obtain characteristics (which are not very accurate, of course), for the reflectivity of the substance of the dark bands (Table 4.2).

TABLE 4.2. BRIGHTNESS COEFFICIENTS OF THE DARK SUBSTANCE IN THE EQUATORIAL BAND ON JUPITER IN 1962.

Light Filter	λ_{eff},Å	r_{da}	Light Filter	λ_{eff},Å	r_{da}
Red	6250	0,69	Blue	4230	0,28
Green	5300	0,48	Violet	3770	0,20

The majority of the dark bands has a reddish or brownish coloration which is quite noticeable on the photographs. Sometimes bright orange bands or an orange haze is observed. The orange haze was observed in 1964-1965. As shown in Table 4.3, the contrast between the dark band and the bright zone was already sharply attenuated in 1963.

TABLE 4.3. THE RATIO OF INTENSITIES OF THE EQUATORIAL DARK BAND AND BRIGHT TROPICAL ZONES OF JUPITER IN 1962-1965

Light Filter	1962	1963	1964—1965	Light Filter	1962	1963	1964—1965
Red	0,85	0,89	0,94	Blue	0,60	0,72	0,73
Green	0,73	0,84	0,87	Violet	0,50	0,71	0,72

It should be noted that completely contradictory observational data also exist, in agreement with which the contrast between the dark and bright belts on Jupiter did not increase, but decreased with the transition from red to blue light. This meant that either the dark bands themselves had a more bluish shade in comparison with the bright zones, or that a haze of very fine aerosol /111 was located in the outer atmosphere of Jupiter during this period which led to scattering similar to the Rayleigh type, i.e., which increased in the short-wave region of the spectrum.

We may judge the color of the numerous fine details of the cloud layer only on the basis of visual observations since in fact there has not been a single attempt to investigate photometrically the nature of the development of small formations or to investigate the behavior of changes in brightness and color of such details in the cloud layer. In this respect it is not possible to rely particularly upon visual evaluations. Quantitative data are required which can be obtained only by means of photographs or photoelectric colorimetry or spectrophotometry.

Spectrophotometric measurements of the individual cloud belts of Jupiter and of several details have been accomplished only during recent years [112], [181], [183], but due to the sporadic nature of these observations it is impossible at the present time to determine any regularities in the evolution of the color and reflecting properties of individual cloud formations.

b) The polar regions. The dark regions of the Jovian disk beginning with latitudes 35-40° bear the name polar purely arbitrarily, since the polar regions themselves with latitude > 65-70° are practically inaccessible to observation. The inclination of the Jovian equator with respect to the earth observer may differ from zero by not more than 3°, and therefore the Jovian pole is always located near the limb itself.

The polar regions of Jupiter are interesting first of all because of the presence in them of unusually high polarization. Even with the maximum phase angle of 11°.6, the polarization of light reflected by the entire Jovian disk is very low. However as early as 1929 B. Lyot [126] detected a rather sharp increase in the degree of polarization near the poles of the planet. The degree of polarization near the edge of the disk itself in the polar zone reached 7%. Predominant in the polarized light were vibrations parallel to the polar radius. Near the center of the disk the polarization was negative, which was opposite to the polarization obtained in the polar zone. /112

At the Pic du Midi Observatory A. Dollfus [127] investigated the polarization of Jupiter in various intervals of the spectrum within the region λλ 5300-6200 Å and observed no degree of polarization dependence on wave length. He also determined a sharp increase in the degree of polarization at latitudes greater than 50° (Figure 42), while he also observed changes in polarization properties: in 1955 a polarized region, in contrast to 1952, had a large extention near the north pole and was constricted near the south pole. T. Gehrels and T. Teska [128] discovered that the polarization of the polar regions of Jupiter changes with wavelength in the region from 3250 to 9000 Å (Figure 43).

The degree of polarization of extreme segments of Jupiter which are situated near the equator at the eastern and western limbs of the planet amounts to not more than 3% in the ultraviolet, and in the visible regions, to fractions of a percent. Thus although the polar and equatorial segments of the limb of Jupiter in the period of opposition are under almost identical illumination conditions the polarization of light reflected by these areas is quite different, which must be associated with peculiarities in the structure of the atmosphere and of the cloud layer near the pole and on the equator.

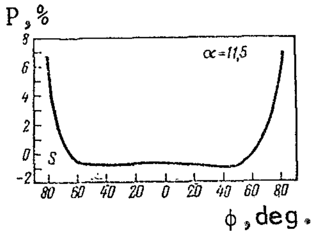


Figure 42. Variation in the Degree of Polarization Along the Central Meridian of Jupiter (After Dollfus).

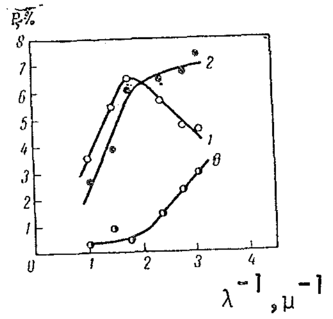


Figure 43. The Degree of Polarization as a Function of Wavelength for the North (1) and South (2) Polar Regions and for the Eastern Equatorial Limb (3) (After Gehrels and Teska).

We shall introduce several assumptions in order to explain the unusually high degree of polarization in polar regions. Lyot believed that it developed as a result of multiple light scattering since the polarization does not depend on phase angle. Light scattering occurs in a purely gaseous atmosphere above the clouds, which according to Gehrels and Teska must have an optical thickness at λ 5500 Å of 0.4-0.8. Dollfus assumes that the polarization is developed by a haze of particles with dimensions of approximately 1 μ. Field and Gaustad [138] advanced the hypothesis that the polar regions of Jupiter contain an accumulation of meteor dust suspended in the atmosphere; the dust assembles near the poles under the influence of the Jovian magnetic field which carries an electrical charge. The /113
mechanism of the formation of strong polarization with practically identical angles of incidence and reflection for the present remains unclear. It is even difficult to explain the great optical thickness of a purely gaseous atmosphere above the polar regions. Although van de Hulst [4] and several

other authors consider it possible that the cloud layer is located at a considerably greater depth at the polar regions than at the Jovian equator, which causes a great thickness of the atmosphere above the clouds, such an opinion contradicts measurement data of the intensity of molecular absorption bands of methane and ammonia. Observations made by the author [36] by the photographic method and by Münch and Younkin [124,125] by the photoelectric method revealed that the intensity of the absorption band of methane CH_4 at 7250 Å, 8860 and 9900 Å drops toward the poles; the ammonia NH_3 absorption band at 6443 Å, according to the observations of Spinrad and Trafton [23] reveals no changes in intensity during the transition from the center of the disk to the poles. Münch and Younkin also assumed that large cloud caps of frozen methane were located above the polar regions of Jupiter. It had been shown previously that attenuation of molecular absorption toward the edges of the Jovian disk could be explained even without the inclusion of the assumption concerning a change in the altitude of the limit of the cloud layer. But in any case it is obvious that a thicker layer of pure gaseous atmosphere cannot be located above the pole and used to explain the unusual light polarization.

c) The structure of the surface of the cloud layer. The resolution of even the most powerful astronomical instruments proves to be several orders of magnitudes below that which would be required in order to examine the structure of the Jovian cloud layer from the earth. Even with ideal instrument resolution (0.02") it is only possible to detect differences in altitude of not less than 60 km; in practice atmospheric turbulence limits the resoluting power of the instrument to an angle of 0.1"-0.2" under the best conditions, so that even a difference in altitudes of cloud formations in hundreds of kilometers would hardly be detected through direct observations. At the same time an investigation of the high-altitude structure of the visible surface of the Jovian clouds presents a great deal of interest in connection with the problem of the nature and the reasons for the circulation processes in its atmosphere.

Several opinions may be introduced concerning the shape of the surface of the cloud layer by utilizing photometric data concerning intensity distribution on the planetary disk. In 1957 Squires [38] suggested that the cloud layer where at least the upper part of the cloud layer consists of tower-shaped elements, i.e., consists of a structure similar to the structure of a field of earth cumulus clouds. The tops of the clouds extend above the basic cloud surface by 20-30 km. Squires needed such a model in order to explain the distribution of methane absorption intensity on the Jovian disk, observed by Hess. However both Squires and Hess, in order to make the model /11
agree with observations, had to assume the presence of daily variations in the altitude of the tops of the cumulus clouds.

The presence in the cloud layer of Jupiter of elements which indicate the convection nature of motions in the troposphere of the planet are quite probable. On the visible surface of the planet it is almost always possible to see dark and bright spots as if penetrating through the cloud layer. But if they also have a different altitude than the upper limit they form the macrostructure of the cloud layer, which introduces no systematic behavior in the change in molecular absorption on the disk. Cloud elements on a scale of several dozens of kilometers, which form the "microstructure" of the cloud surface may play an essential role in brightness distribution and molecular absorption on the disk but it is not difficult to see from Figures 44 and 45 the effect introduced by these elements will be different depending on the relative magnitudes of three parameters which characterize these elements, including the altitude of the cumulus clouds or the bulge h above the base level, the width a of the base of the element and the distance b between clouds. If the values of these parameters are practically identical then even near the limb of the planet itself we shall see the lateral sides of the cloud elements on which the light falls and correspondingly is reflected at various angles α; a rather large amount of light will arrive and be reflected almost along the normal to the lateral surface. It is clear that in this connection limb darkening will decrease in comparison with the even surface of the cloud layer and may even be lacking completely. Molecular absorption in the outer atmosphere in this connection will decrease toward the limbs of the disk or remain constant, since the deepest segments of the outer atmosphere, with the shift toward the limb of the disk, will be screened by the lateral sides of /115 the cloud elements. With other relationships between cloud element parameters, for example ($h \leqslant a$, $h \leqslant b$, $a \simeq b$) or ($b \leqslant h$, $b \leqslant a$, $h \geqslant a$), their influence on limb darkening and molecular absorption will be less. Thus if the assumption of Squires had been correct we would have observed significantly less limb darkening for Jupiter than actually occurs in fact. Since limb darkening on Jupiter agrees sufficiently well with theoretical calculations for a smooth cloud layer there is no basis for believing that the visible surface of Jupiter has a sharply-expressed cumulus-like structure. Nevertheless there is interest, of course, in the presence of well-observed material, in examining several differences in the brightness distribution over the disk from theoretical values and from the point of view of the effects of the "microstructure" of the cloud surface of Jupiter.

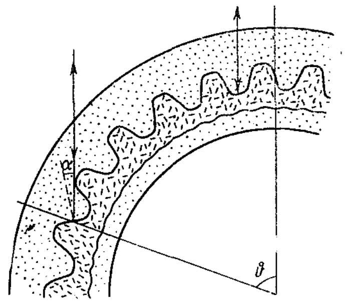


Figure 44. The Reflection of Light from a Cloud Surface Consisting of Tower-Shaped Elements. The angle of reflection α from the lateral sides of the clouds may be significantly less than ϑ

These effects could be detected best of all in the zone of the terminator of the planet, but with observations not from the earth but from space probes where the position of the terminator is close to the central meridian of the disk.

d) The relative altitudes of the upper limits of the cloud belts. Even with a smooth surface of the clouds, their altitude limit for dark bands may differ from the altitude limit for bright zones. From the observed fact that limb darkening for dark bands and bright zones is practically identical, N. P. Barabashov [129,130] came to the conclusion that all cloud formations on Jupiter are at the same altitude. For example if in fact the dark bands were located significantly lower than the zone, the optical thickness of the scattering

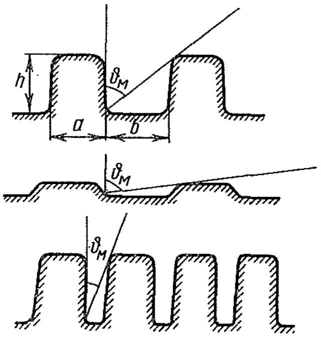


Figure 45. The Maximum Angle of Incidence (and Reflection) at Which a Ray Still Penetrates to the Base of the Clouds.

atmosphere above the clouds in the dark bands would be greater and the illuminating effect of the outer atmosphere would lead to the fact that limb darkening in dark bands would be less than in bright bands. However this is not as obvious as it appears at first glance. Previously we mentioned the fact that in dark bands limb darkening must be less than in bright bands, even without overlapping of light scattering of the outer atmosphere. The greater the coefficient κ_λ of true absorption, i.e., the lower ω, the lower the albedo and the lower the relative limb darkening.

The influence of light scattered by the outer atmosphere may be clarified if we carefully check the relationship of the visual albedo of a given band with value ω, which is determined from brightness distribution (limb darkening). But it would be quite difficult to evaluate here the magnitude of the difference in altitudes of two cloud surface levels only from photometric data. More certain evaluations of this type can be made on the basis of measurements of the intensity of molecular absorption bands in bright and dark regions of the Jovian disk.

At any point in the absorption band the optical thickness of the outer atmosphere equals /116

$$\tau_\lambda = (\sigma + \varkappa_\lambda) \int_{h_0}^{\infty} \rho dh = \rho_0 H_0 (\sigma + \varkappa_\lambda) = \tau_{co} + \tau_{ab}. \tag{4.15}$$

Since in the red and infrared regions of the spectrum, where the intensive absorption bands are located, $\tau_{co} \ll \tau_{ab}$, the value τ_{co} may be disregarded and we may consider only the optical thickness of the outer atmosphere which is determined by the molecular absorption. If the altitude h of the upper limit of the reflecting cloud cover on a certain part of the disk differs from h_0 by the value $\Delta h = h - h_0$, then it is not difficult to show that the optical thicknesses of outer atmospheric layers which are located above levels h_0 and h, in the case of an atmosphere with a vertical temperature gradient G, will be linked by the relationship

$$\tau_{ab}(h) = \tau_{ab}(h_0)\left(1 - \frac{\Gamma \Delta \mathrm{h}}{T_0}\right)^{g\mu/R\Gamma - 1} = D\tau_{ab}(h_0), \tag{4.16}$$

where T_0 is the temperature at level h_0. By using the graphs of this function (Figure 46) and values determined from observations for τ_{ab} in absorption bands for various Jovian cloud zones, it is possible to find the difference in altitudes of these zones with sufficient accuracy, since formula (4.16) is sufficiently responsive to changes in the value Δh and the result shows little change during a change in value T_0, which for the surface of the cloud level, as we already know, equals roughly 160 ± 10°K.

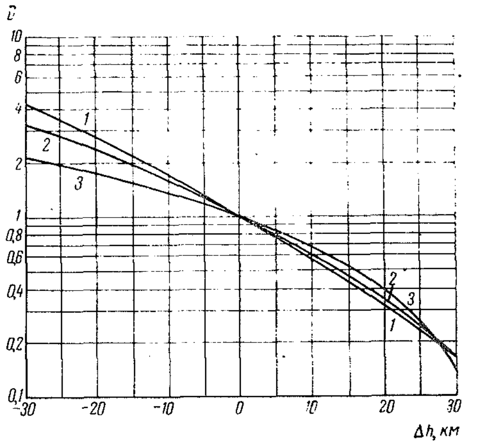


Figure 46. Graphs of the Function $D = (1 - \Gamma\Delta h/T_0)^{g\mu/R\Gamma - 1}$. 1, Γ = 1°K/km; 2, Γ = 2°K/km; 3, Γ = 4°K/km.

If the cloud layer of Jupiter acts only as a reflecting screen the application of such a formula to the processing of the results of observations immediately gives the value of the difference in altitudes. But if molecular absorption occurs in the cloud layer, the determination of the value τ_{ab} becomes more difficult. Then it is necessary to resort to calculations described in Chapter I, and only after establishing the optical thickness of the outer layer itself is it possible to calculate the altitude difference.

Observations of methane absorption bands, accomplished by the author, reveal that divergence in methane absorption between the bright zones and the dark bands of Jupiter is extremely small. According to measurements of the visible region of the spectrum in 1963, it was ascertained that CH_4 absorption is somewhat less in the bright zones, i.e., the dark bands must be located 1-2 km lower than the bright zones [34]. According to observations in infrared light [36] in 1964-1965, it was revealed that the limit of the dark bands is located below the bright bands at a distance of 2-4 km for a single-layer model and at a distance of 5-10 km for a dual layer model of an absorbent atmosphere. According to data furnished by Münch and Younkin [125], absorption in the zones is more intensive than in the dark bands, i.e., the zones are located lower in altitude.

In any case observations of molecular absorption of methane reveal that the altitude difference of the upper limit of the bright zones and the dark belts of the cloud layer of Jupiter do not exceed several kilometers. In /117
connection with these results it is not possible to agree at all with the opinion of Urey [59] and Öpik [50] that the dark bands of Jupiter represent regions of the atmosphere, partially or completely free of clouds, where the atmosphere is transparent to a significantly greater depth than in the cloud zones. In this case the absorption bands in the dark bands would be significantly more intensive and they would also reveal significant intensification toward the limb of the disk, since in an atmosphere deprived of aerosol, molecular absorption would predominate over scattering.

The individual cloud formations may apparently be located at different levels, since multiple instances of overlapping of some details on Jupiter by others have been noted. A special analysis of these cases would probably reveal certain information concerning relative altitudes, but only indirectly according to the rates of displacement of the upper and lower formations [132,133]. According to photographs of Jupiter (colored and obtained with light filters) obtained by the author in 1965, an interesting phenomenon was detected, which proved to be a partial screening of the dark, almost neutral-colored north equatorial band by an orange haze, transparent in infrared light and dark in blue and ultraviolet rays. Due to the haze the appearance of the NEB in infrared light and in blue light was different since in the blue light the haze concealed the uneven southern edge of the NEB. The haze itself had sharply defined limits and was not subjected to the turbulent motion of the clouds noted in the NEB.

This indicated that the haze was located at a great altitude where the nature of atmospheric currents apparently was more calm. Photometric measurements led to the conclusion that the optical thickness of the haze in blue light was approximately equal to 0.3 and the linear thickness of the haze layer was of the order of 10-100 m. /118

e) The optical thickness of the outer atmosphere. The outer atmosphere is clearly outlined in the red and infrared regions of the spectrum by the appearance of molecular absorption bands of methane, ammonia and hydrogen. Whether the outer atmosphere developed any perceptible effects in the continuous spectrum is not known at the present time. If the outer atmosphere consists only of pure gas, or more accurately, a mixture of gases without an admixture of particles larger than molecules, the optical thickness of the atmosphere in the continuous spectrum is determined exclusively by Rayleigh (molecular) scattering and equaled

$$\tau_{c\lambda} = \frac{32\pi^3 (n-1)^2 HP}{3N\lambda^4}, \qquad (4.17)$$

where n is the refractive index; H is the height of the homogeneous atmosphere where $P_0 = 1$ atm; N is the Loschmidt number; P is the pressure in atm at the surface of the cloud layer.

Having established the specific chemical composition of the atmosphere and values H and P it is possible to calculate the optical thickness of the outer atmosphere of Jupiter. Table 4.4 shows values $\tau_{co\lambda}$ for the two wave lengths 3500 and 6000 Å where P = 1 atm and H = 16 km for various ratios between the basic components of the atmosphere--hydrogen and helium. Since where P = 1 atm for hydrogen, $n - 1 = 1.38 \cdot 10^{-4}$, for helium $n - 1 = 0.35 \cdot 10^{-4}$, the relative content of these two gases significantly influences value τ_{co}.

TABLE 4.4. THE OPTICAL THICKNESS OF THE OUTER ATMOSPHERE OF JUPITER WITH PURELY MOLECULAR SCATTERING

$H_2 : He$	$\tau_{\lambda 3500}$	$\tau_{\lambda 6000}$	$H_2 : He$	$\tau_{\lambda 3500}$	$\tau_{\lambda 6000}$
1 : 0	0,256	0,030	1 : 3	0,050	0,006
1,5 : 1	0,126	0,015	1 : 40	0,018	0,002
1 : 1,5	0,078	0,009	0 : 1	0,016	0,002

Tr. Note - Commas indicate decimal points.

A pure hydrogen atmosphere in the ultraviolet would have $\tau_{co} \simeq 0.25$, but in orange and red light, $\tau_{co} \simeq 0.03$. An atmosphere with a predominance of helium would be more transparent. Since a pure hydrogen atmosphere does not satisfy data concerning the average molecular weight and must contain at least the same quantity of helium as hydrogen, we may assume that in the visible /119 and near ultraviolet range of the spectrum the optical thickness of a pure gas outer atmosphere does not exceed 0.1.

There is available very little observational data concerning the transparency of the outer atmosphere of Jupiter, while existing estimates of the value τ_{co} do not deserve a great deal of trust.

Thus Van de Hulst [3,4] obtained values $\tau_{co} = 1.3\text{-}0.8$ at 3,500 Å, based on the unpublished results of measurements of limb darkening of the Jovian disk accomplished by Kuiper. In this connection it was assumed that the cloud layer of Jupiter reflects light according to the Lambert law and that observed deviations from this law in brightness distribution on the disk may be attributed to the effect of the scattering outer atmosphere. This is not correct since theoretical calculations of brightness distribution for an atmosphere with $\tau = \infty$ (of the cloud layer) gives curves which differ from the Lambert cosine curves.

Through the use of rather coarse average photometric characteristics of dark and bright cloud bands of Jupiter, Öpik [50] determined a value for the transmission coefficient of the outer atmosphere in blue rays of $p = 0.8$, from which $\tau_{co} = 0.23$. He considers the outer atmosphere to be strongly absorbent with $\omega = 0.57$ on the basis of the fact that limb darkening in the dark bands is less than in the bright bands. The dark bands, according to Oepik, are regions free from clouds and their brightness is determined by true absorption in the interior of the layers and by scattering in the outer atmosphere. Under such an assumption there is no requirement, as we have seen previously, that darkening of the limb must be less for dark cloud belts than for bright cloud belts, even without the participation of the outer atmosphere.

Of not much better basis were the results of Yu. V. Aleksandrov [123] (in blue light τ_{co} = 0.1-0.2) and M. F. Khodyachikh [131] (in red light τ_{co} = 0.2-0.8), who also examined differences in limb darkening in the bright and dark belts as the consequences of overlapping light scattering of the outer atmosphere.

Although τ_{co} estimates are quite contradictory they all furnish values which noticeably surpass those which would be required for a purely gaseous external atmosphere. Therefore at the present time it is impossible to state categorically that in the outer atmosphere there is no aerosol present which forms a light haze. It is also impossible to say anything definite concerning the nature of the dependence of τ_{co} on wavelength. Additional specially organized investigations, both photometric and spectral, are required. Photometric investigation of the Jovian disk in various rays must establish whether a dependence exists between the albedo of the clouds of the bright and dark bands and limb darkening in these bands of theoretical dependence between ω and A for various values of parameter x_1, which characterizes the scattering indicatrix. It is possible to show theoretically what /12
influence an atmosphere of infinite optical thickness exerts on brightness distribution on the disk and on the reflectivity of zones and bands. Spectrometric observations must establish how the contrast between dark and bright formations changes on the spectrum. By using the entire aggregate of observational data and theoretical calculations it is at least possible to clarify the magnitude of the aerosol component in the outer atmosphere and to establish whether it exists at all. It cannot be excluded that in the Jovian stratosphere the temperature changes with altitude in a complex manner, forming zones of temperature inversion where the formation of constant of temporary layers of haze is possible from sublimation products of ammonia or some other gases, similar to the formation of noctilucent clouds at altitudes of approximately 80-85 km in the earth's atmosphere.

Unfortunately we still do not know the behavior of cloud particle spectral reflectivity in the near and far ultraviolet. Probably therefore we should not unconditionally accept the interpretation of the increase in the albedo of Jupiter in the region 3000-2000 Å on the basis of light scattering alone in the hydrogen outer atmosphere as Stecher did [26].

§5. The Red Spot--Optical Properties

a) The shape and dimensions of the Spot. In the southern hemisphere of Jupiter at a latitude of approximately 22°.5 there is an exceedingly unusual, unique formation which has received the name of the Great Red Spot. In contrast to all other details it has been preserved almost unchanged for a period of at least 100 years, i.e., during the course of the entire period of sufficiently reliable telescopic observations of Jupiter. It is possible that the "observation age" of the Red Spot may be increased to 300 years if we identify it with a spot represented on the drawings of Hooke, made in 1664-1672. Although the Red Spot is not visible every year it always appears at the same latitude, displaying only longitudinal shifts. Therefore it may be considered as a quasi-stationary phenomenon on Jupiter. Such types of formations include, and then only conditionally, a very small number of details on the visible surface of Jupiter which in dimensions and other properties cannot be compared with the Red Spot. The physical nature of the Red Spot remains a riddle up to the present time. Here we shall merely state the information concerning the Red Spot which has been obtained as a result of study of its optical properties. We shall again return to the Red Spot in the next chapter in connection with the dynamic properties and the origin of this phenomena.

In many photographs and drawings of Jupiter the Red Spot is represented /121 in form of an oval, extended in longitude. In fact the configuration of the Spot did not correspond exactly to an oval or to an ellipse. With the best image quality it may be seen that the eastern and western edges of the Spot are elongated and have sharp ends. This peculiarity in the shape of the Red Spot has for some reason received no attention although it may be of essential significance in the problem concerning the physical nature of the Spot.

The Red Spot occupies approximately 25° in longitude and about 10° in latitude. The major axis of the Spot has a length of up to 40,000 km, in the minor axis approximately 13,000 km. The visible compression of the Spot in latitude is caused only in a small degree by perspective reduction ($\cos \phi_{RS} = 0.924$) and basically reflects the actual configuration of this formation. The shape and dimensions of the Red Spot from year to year show practically no change, as far as can be judged according to numerous drawings from different years. It is true that in certain years the Spot was narrower and extended to a greater degree in longitude than was ordinarily the case. This is apparent, for example, on photographs of Jupiter obtained at the Lick Observatory in October 1927 (Figure 47). The usual appearance of the /122 Red Spot on photographs is shown in Figure 48. In 1964-1965 the length of the Spot on the average was approximately 27,200 km, and the width was about 13,400 km.

The Red Spot is situated between the south temperate belt (STB) and the southern component of the SEB, while the distance between the borders of the SEB is usually less than 10°. In this case the southern edge of the Spot touches the STB or even encroaches upon it somewhat. But the Spot does not come into contact with the SEB but seems to push this belt away from it. A hollow forms in the SEB which is an oval depression in which the Spot is submerged by approximately one-third of its minor axis. There is almost always a bright interval between the Spot and the belt. Such a reaction characteristic of the Red Spot with adjacent bands on the north and on the south must be taken into consideration in the development of any hypothesis regarding the nature of this formation.

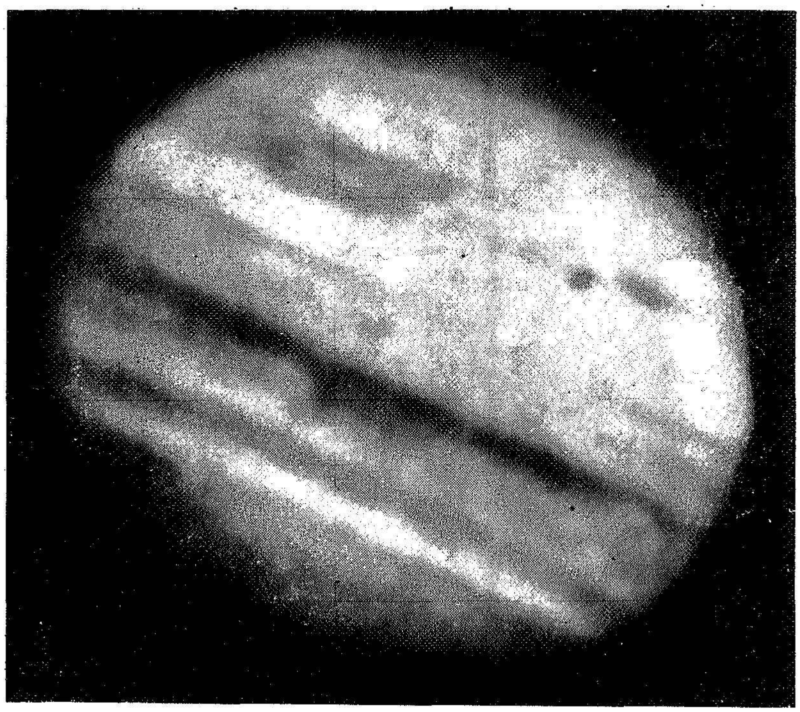


Figure 47. A Photograph of Jupiter in October 1927. The Red Spot is spindle-shaped and displays extremely non-uniform brightness.

b) Visibility of the Red Spot in different years. At times the Red Spot is the most noticeable object, especially in blue light, on the Jovian disk, /123 but there have been years when the Spot was missing. But in this case the depression of the Great Red Spot in the SEB remains visible which testifies to the presence of a disturbance in the atmosphere at this location. It is still difficult to give any explanation for the disappearance of the Spot itself. Perhaps it is covered by overlaying clouds, but it is more probable that the Spot changes its color and for some reason becomes an object which is colored identically with the surrounding cloud layer.

Figure 49 shows a visibility graph of the Red Spot in the period from 1892 to 1947, plotted according to a summary by Peek [102]. The visibility of the Spot is evaluated on a 9-point scale (0 is invisible, 1 is very weak, 4 is quite noticeable, 6 is easily distinguishable, 8 is very dark). Of course this scale is quite arbitrary especially since the evaluations of various observers are frequently contradictory. Nevertheless when we are dealing with changes in visibility points from year to year by several units, such changes may be considered to be real. The Red Spot was most intensive in 1927 and in 1937-1938. However its disappearance, which can be seen from the graph, occurs independently of its intensity during the preceding year.

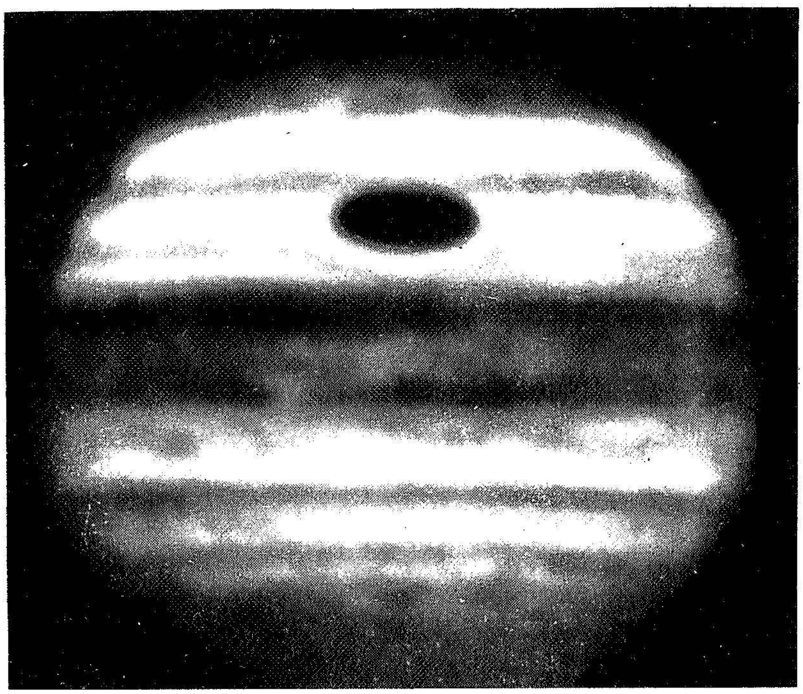


Figure 48. A Photograph of Jupiter in 1964 in Blue Light (After B. Smith).

c) Photometric and spectral properties. It is possible to find many descriptions of color characteristics of the Red Spot in summaries of visual observations of Jupiter. The most diverse evaluations of this color are encountered; from intense pink to brick red and grey. Unfortunately in connection with the importance of the information concerning the color of the Spot and its changes, it is not possible to rely on visual evaluations, which are affected by psychological and physiological effects.

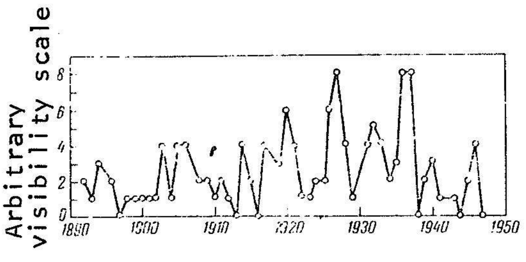


Figure 49. Visibility Graphs of the Red Spot in 1892-1947 According to a Summary by Peek [102].

The coloration of the Red Spot is not uniform: usually the edges, especially the eastern and western edges seem to be darker or more intense in color than the middle.

The red or red-orange color of the Spot is confirmed by color photographs of Jupiter, by photographs in various rays and by spectrograms. On photographs in red and infrared light the Spot disappears, or more exactly, it assumes the appearance of the bright region between the dark bands on its borders.

In green light the Red Spot appears to be approximately just as dark as the neighboring STB and SEB. In blue, violet and ultraviolet light the Red Spot proves to be significantly darker than the belts (Figure 50). It is possible to make a quantitative judgment of the magnitude of the contrast of the Red Spot with the surrounding surface according to photometric profiles of the Jovian disk, made along the Spot parallel when the Spot was located near the central meridian (Figure 51). Table 4.5 shows that relative brightness values of the Spot according to photographs obtained by the author in 1962. The most complete characteristic of the color properties of the Red Spot may be given by spectrophotometric measurements. We may judge according to these measurements changes in the coloring of the Spot and the presence of absorption bands for substances present in the Spot. Obtaining spectrograms of the Spot is not difficult and it is surprising that until recent times the Red Spot was not studied with spectrophotometric methods. The author frequently succeeded in obtaining satisfactory spectrograms of the Spot with a dispersion of 30 Å/mm, but the best results (due to short exposures of the order of 3-30 sec) were obtained in 1964 with the 70-cm reflector of the Astrophysical Institute of the Academy of Sciences of the Kazakh SSR with a prism spectrograph with a dispersion of 143 Å/mm at H_γ, installed at the 11-m Cassegrain focal point. With the orientation of the slit of the spectrograph along the parallel of the Red Spot the spectrum of the Spot and the spectrum of the surrounding zone of the disk were obtained on the spectrogram (Figure 52). The spectral curve of the Red Spot in relation to the adjacent bright zone (Figure 53) revealed that the spot becomes darker than the zone at $\lambda\lambda \leqslant 6100$ Å. In the band of wavelengths 6300-4500 Å relative intensity behavior becomes almost neutral, so that in the violet and ultraviolet rays the Red Spot seems to be almost indentically dark. This is also detected on photographs. At the present time it is not possible to say what this phenomena is linked with or whether it is a property of the substance which /125

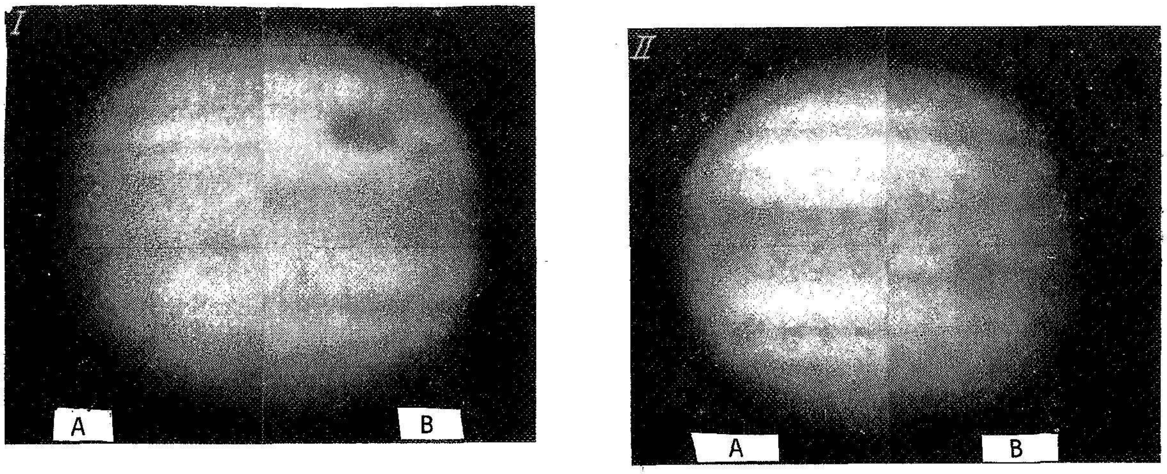


Figure 50. Photographs of Jupiter Showing the Red Spot in Various Colors, Composite Halves. A, in red light; B, in blue light.

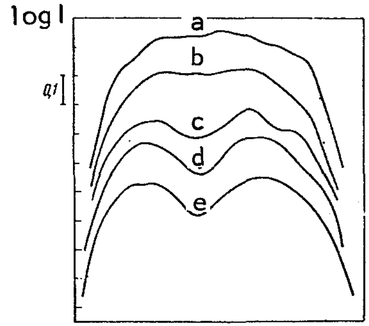


Figure 51. Photometric Profiles of the Red Spot and the Jovian Disk Along the Parallel $\phi = -22.5°$ at Wavelength 5900 Å (a), 5700 Å (b), 4850 Å (c), 4450 Å (d) and 4100 Å (e).

forms this Spot or an effect of the overlapping of light scattered in the outer atmosphere.

Visual observations reveal that with an approach to the edge of the disk the Red Spot becomes less noticeable. This is also detected in conjunction with photometric scanning of photographs of Jupiter. The maximum drop in the contrast between the Spot and the surrounding background is observed in short-wave rays. While investigating how the relative brightness of the spot changes toward the edge of the disk, we may clarify whether the photometric properties of the Red Spot differ from the properties of the surrounding cloud layer and the magnitude in principle of this difference and whether or not it indicates a different physical nature for the Spot than for the surrounding cloud layer.

Contrast measurements of the Red Spot were made for the first time in yellow and orange light at various distances from the central meridian at the Astrophysics Institute of Academy of Sciences of the Kazakh SSR in 1957 by G. M. Nikol'skiy [134]. However due to the excessively small diameter of the images and excessive band widths of the light filters the results proved to be insufficiently reliable and led to an incorrect conclusion involving very high true absorption ($\omega = 0.4$) in the Red Spot in the spectrum region λλ 5000--5600 Å in comparison with the region λλ 5000-6000 Å

In 1962 similar observations were accomplished by the author [135], but with sufficiently large image diameters (6 mm) and with various light filters. These observations revealed that true absorption in the spot increases smoothly toward the short waves: $\omega = 0.96$ in red light, $\omega = 0.92$ in green and $\omega = 0.88$ in blue light. Spot contrast decreases toward the edge in approximately the same way that it must decrease if the Spot in the same mixture of gas and aerosol as the surrounding cloud layer. Only aerosol possesses a somewhat greater true absorption in the short-wave band of the spectrum.

TABLE 4.5. RELATIVE BRIGHTNESS OF THE CENTER OF THE RED SPOT IN COMPARISON WITH THE SOUTH TROPICAL ZONE IN 1962

Filter	λ_{eff},Å	I_{rs}/I_{STZ}	Filter	λ_{eff},Å	I_{rs}/I_{STZ}
KC-10	6250	0,96	CC-5	4400	0,69
3C-1	5300	0,77	ФС-7	4050	0,60

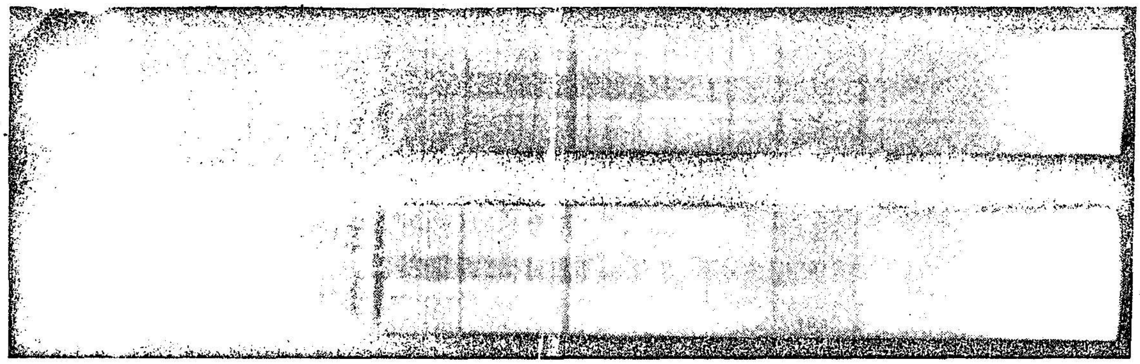


Figure 52. Spectrograms of the Red Spot.

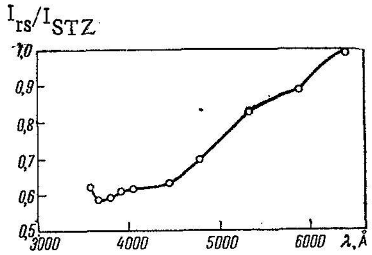


Figure 53. The Relative Spectral Curve of the Red Spot I_{rs} in Comparison with the South Tropical Zone I_{STZ}.

Spectrophotometric observations in 1964 [152] lead in general to the same result (Figure 55), however we obtain more clearly than from photographs a certain deviation in the observed change in relative intensity of the Spot from that calculated theorectically; Spot contrast drops toward the limb somewhat more rapidly than it should according to theory [152]. Such a deviation may be the result of various causes. The measurements themselved of the Spot near the edge of the disk may reveal a certain systematic error tending toward a contrast reduction due to difficulty in determining the center of the Spot. The appearance of effects associated with light scattering in the outer atmosphere is possible at the edge of the disk. Finally, the optical parameters of the substance of the Red Spot are certainly not obligated to correspond exactly to those accepted in theorectical calculations. But one way or another photographic and spectral observations have revealed that the Red Spot is a gaseous-aerosol formation and in optical properties does not differ fundamentally from other cloud details on Jupiter.

d) The altitude of the upper limit of the Red Spot. The surface of the Red Spot cannot be located significantly above the surface of the surrounding cloud layer because partial screening of the Spot by clouds passing over it has been observed repeatedly. If the Spot were situated considerably below the limit of the cloud layer, let us say, close to the base of the atmosphere, then this could be detected by measuring the value of the perspective distortion of the Spot toward the edge of the disk--somewhat similar to the well known Wilson effect for sun spots.

Let us assume that the Spot, with angular length of the major axis 2β, is situated at altitude h below the surface of the cloud layer (Figure 55). It is not difficult to show that the visible dimensions of the Spot when it is located at angular distance ϑ from the center of the disk will equal /129

$$a = AD = GE - FK = 2R \sin\beta \cos\vartheta - h \sin(\beta + \vartheta) \tag{4.18}$$

or

$$\frac{a}{R} = 2\sin\beta\cos\vartheta - \frac{h}{R}\sin(\beta + \vartheta). \tag{4.19}$$

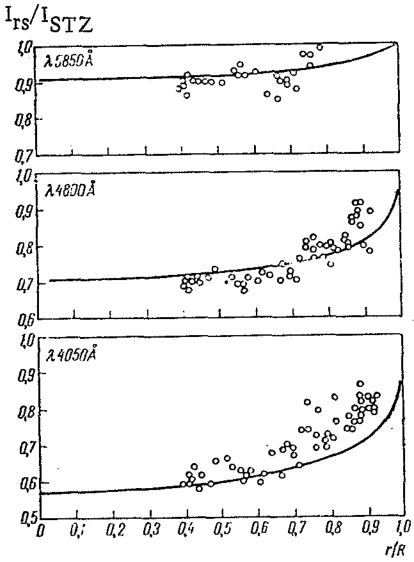


Figure 54. The Change in Relative Intensity of the Red Spot Toward the Edge of the Disk According to Spectrophotometric Measurements. The continuous lines are theoretical curves.

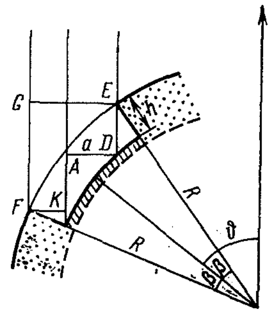


Figure 55. The Effect of Possible Unusual Perspective Reduction of the Red Spot, Observed if the Spot were Located at a Great Depth.

The effect of unusual perspective reduction of the Spot will be noticed only when value $h/R \sin(\beta + \vartheta)$ amounts to not less than several percent of the value $2 \sin\beta \cos\vartheta$. If we can register an anomaly at 5% of the value of the major semi-axis, then the condition for the detection of this effect will be

$$\frac{h}{R}\sin(\beta+\vartheta) \geqslant 0{,}1\sin\beta\cos\vartheta, \tag{4.20}$$

from this

$$\frac{h}{R} \geqslant \frac{0{,}1}{1+\operatorname{cotan}\,\beta\tan\,\vartheta}. \tag{4.21}$$

Where $\beta = 13°$ and $\vartheta = 60°$ we obtain $h \geqslant 0.01\,R$, i.e., a 5% deviation from the normal perspective reduction of the major axis of the Spot may be detected if the depth of the Red Spot is not less than 700 km. It is clear that we cannot distinctly see a formation which is situated at such a depth in the Jovian atmosphere if only due to light scattering in a pure gaseous atmosphere. Therefore micrometer measurements of the Spot can hardly give any kind of information concerning its relative altitude.

It is necessary to recall the spectral method of determining relative altitudes from the intensity of molecular absorption bands. The most suitable for this purpose is the CH_4 absorption band at 6190 Å. The superiority of this band consists of the fact that it is located not far from the limit where the increase in true absorption begins in the Spot. Although at wavelength 6190 Å the Spot is not visible it already becomes noticeable at λ 6000 Å, so that identification of segments of the disk which correspond to the Spot /130
in the CH_4 band at 6190 Å is not difficult.

According to measurements made by the author in 1962 [136] the intensity of the CH_4 absorption band at 6190 Å in the Red Spot with an accuracy of ±0.01 does not differ from band intensity in the South Tropical Zone ($\bar{R}_{ab}$ = 0.22). If we employ the graph (Figure 46) then in the final analysis we find that the altitude difference between the limit of the Spot and the surrounding clouds cannot be greater than 3-5 km.

The author also investigated spectrograms of the Red Spot in 1964-1965, in accordance with which the intensity of the CH_4 methane band at 6190 Å and a segment of the NH_3 band near λ 6475 Å was measured [184]. It was determined that the equivalent width of the CH_4 band in the Red Spot equaled 20.2 ± 0.4 Å while the width in the South Tropical Zone was 22.5 ± 0.5 Å; the equivalent width of the NH_3 band were 1.13 ± 0.16 and 1.08 ± 0.17 Å, respectively. Thus as far as molecular absorption is concerned there is no significant difference between the Red Spot and the surrounding cloud layer.

With the data presented here we have truly exhausted available data concerning the optical properties of the Red Spot. We shall point out only one other peculiarity. While measuring the radiometric temperature of individual segments of the Jovian disk Murray, Wildey and Westphal [80] discovered that the temperature of the Red Spot is lower than the temperature of the surrounding cloud background by 1.5-2.0°K (Figure 56). Since the radiometric temperature pertains to the atmospheric level above the clouds it is difficult to say how this must be associated with the surface temperature and other physical characteristics of the Spot. The temperature of the Red Spot itself, or at least the difference between the temperature of the Red Spot and the surrounding clouds could have been established by means of measuring the intensities of the rotational lines of methane and ammonia in the absorption band.

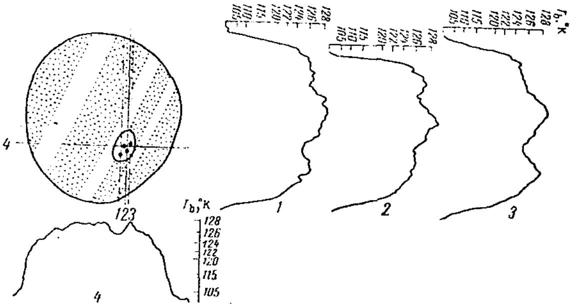


Figure 56. Temperature Profiles of the Jovian Disk and the Red Spot (After Murray, Wildey and Westphal).

As mentioned above the lack /131 of a significant difference in the intensity of the NH_3 band at 6475 Å in the Spot and in the South Tropical Zone precisely indicates that the difference in temperatures must not exceed 2°K, since the total NH_3 content under saturation conditions in the atmosphere near the cloud layer is quite responsive to temperature fluctuations.

§6. The Nature of Cloud Level Particles

a) Ammonia--The most probable cloud substance. While examining various questions concerning the structure of the atmosphere in the cloud layer of Jupiter, we proceeded from the assumption that the Jovian clouds consist of frozen ammonia crystals. This assumption has been in existence for many decades and has been disputed by no one, although we have practically no observational data which directly indicates the ammonia nature of the cloud particles and therefore proceed only from indirect considerations.

Ammonia is a natural gas from known components of the Jovian atmosphere which has the relatively high melting point -78°C (195°K) and boiling points -33°C (240°K), i.e., it may be found under Jovian atmospheric conditions in the solid and liquid phases. Almost all of the temperature evaluations cited in preceding sections for the cloud layer have resulted in lower value than the NH_3 melting point. Since the pressure at the surface of the clouds must be of the order of 1 atm, there is sufficient foundation to believe that at least the upper zone of the cloud layer must contain a large quantity of solid particles--crystals of ammonia ice. With immersion in the depths of a cloud layer, i.e., with an increase in pressure, the balance between the solid and gaseous phase of ammonia must yield to a balance between the gaseous and liquid phases, i.e., the deep sections of the cloud layer must consist of ammonia drops.

Spectrometric recordings of the infrared spectrum of Jupiter, accomplished with the balloon-borne telescope "Stratoscope-2", revealed a strong absorption band near λ 3 μ. This absorption may be partially caused by gaseous ammonia, but in order to provide the band intensity required it is necessary that the outer atmosphere of Jupiter contain not less than 40,000 cm-atm of gaseous NH_3, which contradicts all determinations of ammonia content. Danielson [74] notes that laboratory investigations have established the presence in solid ammonia of an absorption band of approximately 3 μ. Thus the presence of such an absorption band in the Jovian spectrum may be considered as the first direct indication of the possibility of the ammonia nature of the cloud layer. While it is true that the same spectral region also contain a water ice absorption band, the presence of water in the outer layers of the Jovian atmos- /13
phere is not possible.

b) Possible sources of coloration and the reasons for color changes in cloud formations. Ammonia crystals themselves are not capable of a sharp change in coloration. Therefore if the cloud layer of Jupiter consists mainly of ammonia crystals there must be a sufficient quantity of other chemical compounds contained in them whose presence may explain the various color shadings observed on the visible surface of the Jovian cloud layer. Recently attempts have been made to explain color differences on Jupiter by the effects of light and absorption scattering in the outer atmosphere [147,148, 125,149]. In this connection it is assumed that the entire cloud cover of Jupiter is gray, neutrally reflecting, in which only differences in albedo occur, but not in color. Although in principle this case may be considered, it does not facilitate solving the problem of the nature of the cloud layer; on the contrary, it brings up the necessity of explaining first of all why the Jovian clouds differ in albedo, and secondly, what substances in the outer atmosphere develop the effect of intensive coloration in individual cloud details and bands.

Laboratory experiments revealed that certain substances may be tinted in various colors depending on temperature.

In 1939 Wildt [60] expressed the proposal that color differences on Jupiter may be caused by admixtures of small quantities of sodium, dissolved in ammonia. In the laboratory such a solution of sodium and liquid ammonia reveals the following interesting phenomena. At a temperature of 195°K ammonia begins to congeal from a dilute solution. When the temperature is further reduced by 2°, a large part of the NH_3 is transformed into a crystalline state. In this connection the remaining solution becomes more concentrated and assumes a bronze shade, which is intensified in proportion to solution saturation. But before the saturation point is reached the freezing point of the solution is sharply reduced and the solution does not crystallize until the temperature reaches 161°K. The crystals obtained acquire a lead shade with a metallic glint. If we now examine the inverse process of heating the crystals of a sodium solution, we see the following. As soon as the temperature rises above 161°K, several crystals will be transformed into drops of concentrated solution which have a clear, reddish-bronze shade.

In this connection a majority of the crystals will still remain in the solid state until the temperature reaches 32°. Between 193 and 195°K the remaining crystals liquify. With a further increase in temperature the solution is divided into two phases with different concentrations and densities. The lighter component has a bronze tone and the heavier component has a blue coloration. The relative quantity of these phases depends on sodium concentration /133 in the solution. If the solutions consists of 4.15% sodium atoms and 95.85% ammonia molecules, two phases may exist until the critical temperature rises by several degrees.

Thus if the temperature of the surface of the cloud layer is below 161°K, cloud particles may consist of small crystals of ammonia and small crystals of a sodium solution which are gray in color. In areas where the temperature is above 161°K there may be present in the clouds drops of a solution which will impart to the clouds a pinkish or brownish shade. Peek [102] notes that similar color effects may be furnished by solutions of other alkaline metals in ammonia. However the hypothesis of Wildt encountered objections associated with the high chemical activity of sodium. While entering into chemical reactions atmospheric sodium would not be able to maintain the color characteristics of individual segments of the planetary cloud cover for a long period.

Hydrocarbon and hydronitrogen chemical compounds more complex than methane and ammonia may also impart diverse coloration to cloud particles, depending on temperature. The experiments of Sagan and Miller, described in Chapter 1, revealed the possibility of the formation of high molecular weight compounds and complex molecules in a mixture of hydrogen, methane and ammonia during electrical discharges. Rice and Cosgrave [140] also discovered by means of laboratory experiments that a N_2O_3 precipitate of blue coloration forms during the transmission of an electrical discharge through ammonia. Rice [141] obtained in the laboratory a number of selectively absorbent compounds which exist only at extremely low temperatures--below 148-78°K. A yellow color was displayed by compounds $(NH_2NH)_n$, CH_2S, $(CH_3CH_2)_2N$, a blue color by a $(NH)_n$ compound, a bright green color by $(CH_2)_2N$, and a red color by $(CH_2)_3CS$. Rice believes that a basic role in the coloration of Jovian details may be played by frozen free radicals of the CH and NH type which are not encountered under earth conditions which form only intermediate links in chemical reactions. In the outer Jovian atmosphere free radicals may form under the influence of solar radiation on the day side, while they may freeze on the night side and settle out at the level of the cloud surface. In this connection non-uniformity in the coloration of the visible surface of Jupiter may be explained by the fact that different substances usually are located at different levels of the cloud layer and are only sporadically carried to the surface by atmospheric convection currents. Such a hypothesis was proposed by V. G. Fesenkov [142] who suggested that the bright bands might consist of ammonia condensation products and the dark bands of other chemical compounds, brought out of the deeper layers by convection currents.

Rice believes that the Red Spot could have been formed as a result of the appearance on the surface of an acetylene polymer, formed during the irradiation of methane by short-wave radiation (Urey [143]) or during intensive electrical discharges [139]. /134

There is no shortage in attempts to explain the colors of the cloud details of Jupiter. Thus M. Briggs [144] advances the proposal that the pink shade is created by certain organic unsaturated compounds synthesized from atmospheric gases again under the influence of electrical discharges in containing substances of the chromophore groups. H. Papazian [145] even proposed the hypothesis that the coloration of Jovian cloud zones developed as a result of bombardment by solar protons. It would be possible to mention a number of other similar hypothesis [146]. However even the most meaningful laboratory experiments are unable to furnish the solution for the problem of the composition of the particles of the Jovian cloud layer. It is necessary to study very carefully the spectral reflecting properties of individual colored zones of Jupiter and to compare these with the properties of various chemical compounds. Particular attention must be paid to investigation of absorption bands in the continuous spectrum, mainly in the ultraviolet, where it must be acknowledged that such investigations are hindered by the tremendous quantity of overlapping Fraunhofer lines. Careful investigation of ultraviolet absorption of a variable nature is required. It may be associated with the presence of some specific substance, the quantity of which changes with time. Perhaps it will be possible to trace some kind of regularity in these changes for the various zones of the disk. But in any case in interpreting observations we must consider that we are dealing not with pure substances, but with mixtures.

We cannot completely exclude still another possibility in the formation of coloration in cloud details, associated with specific particle dimensions. It is true that in this case the medium would have to be monodispersed, i.e., in a given zone the particles would have to be of a rigidly specified dimension, a situation which in practice is practically never encountered.

c) The probable dimensions of cloud particles. For the present it is not possible to say anything definite about the dimensions of particles of the Jovian cloud layer since special investigations have not been conducted. An anology with earth clouds in this respect would hardly have any meaning, since particle dispersion with respect to dimensions is relatively high and depends on cloud altitude and phase. If we could determine the scattering indicatrix in the Jovian cloud layer then in accordance with its shape it would be possible to judge the dimensions and several other properties of cloud particles. Unfortunately it is practically impossible to determine the complete indicatrix for Jupiter by means of earth observations alone. It is possible only to select parameters which satisfy observations within limited phase angle intervals. According to results obtained by Yu. V. Aleksandrov [149] the average particle dimensions for the Jovian cloud layer are $r = 0.075 \pm 0.005\ \mu$. /135

In terrestrial clouds of the lower and medium level, the average radius of a drop equals ~ $5\ \mu$ [150]. In argentous clouds, in agreement with measurements of their photometric properties (C. Villman [151]), the average particle radius is r = 0.11-0.15 μ. According to rocket experimental data on obtaining matter of argentous clouds, the lower limit of the dimensions of the condensation nuclei of these clouds is approximately 0.05 μ..

If particles of the Jovian cloud layer have a mean radius of approximately 0.1 μ, it is possible to calculate how long these particles may be maintained in a comparatively narrow range of altitudes. For this purpose we utilize the well-known formula of Stokes for the rate of fall of spherical particles in a viscous medium:

$$v = \frac{2g\rho_k}{9\eta} r^2, \tag{4.22}$$

where g is the acceleration of the force of gravity; ρ_k and r are density and particle radius; η is the coefficient of viscosity. Then for Jovian conditions (P ≃ 1 atm, g = 250 cm/sec^2, $\eta = (7\text{-}11.5)\cdot 10^{-5}$ g/cm sec, $\rho_k =$ $= 0.82$ g/cm^3), we obtain where r = 0.1 μ, a rate of fall of less than 0.001 cm/sec. This means that a particle would descend 1 km in 10^8 sec, or in approximately 3 years. It is clear that insignificant rates of travel for ascending atmospheric currents are sufficient to allow particles of the Jovian cloud layer to be maintained at a constant altitude for an indefinitely long time.

Theoretically we may predict the probable particle dimensions at a given level of the cloud layer by considering equilibrium between particle rates of evaporation and condensation. But since the atmospheric parameters are not known with sufficient reliability, these calculations would be too speculative. Photometric determinations, in addition to the difficulties involved, are associated with the fact that we are not able to observe Jupiter at various phase angles, and also we cannot arrive at a unique result with respect to particle dimensions because in addition to particle dispersion with respect to dimension we do not know the particle shape. Ammonia crystals are included in the cubic system but calculations are usually accomplished for spherical transparent or non-transparent particles so that they may be applied more readily to drops rather than small crystals.

It would be extremely important to obtain observational data not so much pertaining to the dimensions of the Jovian cloud particles, but rather pertaining to the existing phase of the particles and the volume density of the cloud matter.

CHAPTER 5. /136

CIRCULATION AND ACTIVE PROCESSES IN THE ATMOSPHERE

§1. The Rotation of the Cloud Layer and the Outer Atmosphere

a) The speeds and periods of rotation of the cloud zones from visual observations. The problem of the overall circulation of the Jovian atmosphere is in fact completely undeveloped. Its solution requires both careful and systematic observations, as well as serious theoretical investigations pertaining not to astrophysics, but rather to hydrodynamics and aerodynamics and the mechanics of rotating bodies. Observational data which the investigator now uses in an attempt to analyze the dynamic properties of the Jovian atmosphere are based almost entirely on visual observations, mainly by amateurs in astronomy. Up to the present time the single attempt to systematize all these observations is Peek's book [202]; however, the author does not attempt to use the tremendous amount of observational material introduced for the construction of even a tentative overall plan of the atmospheric circulation on Jupiter. Numerous articles also contain, as a rule, only resumes of observed periods of rotation of various Jovian zones and data concerning the displacement of individual details. Only a few works are available in which the possible reasons for equatorial acceleration on Jupiter or the hydrodynamic properties of the atmosphere are discussed. Instability in atmospheric processes on Jupiter, which appear in the rapid variability of the planetary cloud cover, has only recently become an object of serious investigations. But regularities in non-stationary processes on Jupiter have still not been studied. The mechanism which causes stormy activity in the Jovian atmosphere has also not been studied. Here we shall examine in general the observational aspects of the problem of the overall circulation and of non-stationary processes on Jupiter.

It is known that the visible cloud layer and the atmosphere of Jupiter may be divided by rotation rate into three zones: the equatorial (within latitude limits ±10-12°), the rotation period of which is $P_I = 9^h50^m30^s.003$ and the two temperate zones, the north and the south (with $\phi > 12°$) with a /137 rotation period $P_{II} = 9^h55^m40^s.632$. Thus the equatorial cloud formations rotate more rapidly than the clouds of the planetary temperate belts. The values of the rotation periods cited here are employed in astronomical ephemerides in order to calculate the longitude of the central meridian in the I and II systems. The angular velocity of Jovian rotation in the I system equals $1.77 \cdot 10^{-4}$ rad/sec, and in the II system, $1.76 \cdot 10^{-4}$ rad/sec. From this the linear velocity of rotation at the surface of the cloud layer on the equator is 12.64 km/sec, and at a latitude of 12° in the II system, 12.26 km/sec. Toward the poles the linear velocity naturally drops in proportion to the radius of rotation.

The real rotation rates and periods of the individual cloud belts of Jupiter may fluctuate within certain limits although the essential difference between the I and II systems is always maintained. Figure 57 shows a diagram of distribution by latitudes of the periods and angular velocities of rotation, compiled from resumes cited by Peek in [102]. The diagram shows mean values of rotation, and the limits in which they may change, judging by data from various observers taken in different years. The fundamental zones and belts are indicated on the graph. Certain individual details (spots) and local atmospheric currents are designated with numbers.

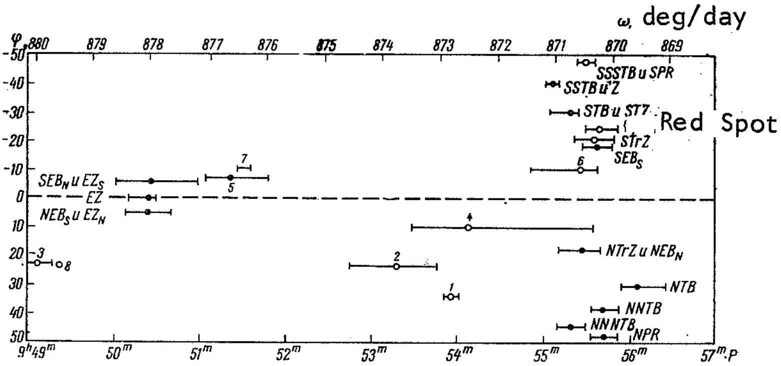


Figure 57. The Periods and Angular Velocities of Rotation of the Cloud Layer of Jupiter at Various Latitudes. 1, Dark spots and bulges on the S-edge of the NNTB; 2, Current B in the NTB; 3, Current C in the NTB; 4, Spots in the middle of the NEB; 5, Current B in the EZ; 6, Spots in the middle of the SEB; 7, White spots in the SEB (1900-1903); 8, Dark spot, 1964. [Translator's Note: u = "and"].

Atmospheric flow rates change in a far from symmetrical manner with respect to the Jovian equator. The southern component of the SEB and the north temperate belt (NTB) rotate most slowly. /138 In the northern latitudes, predominantly in the northern hemisphere, cloud details have been noted many times which are in motion much more rapidly than the equatorial zone itself. Such a detail--a small dark spot--was observed last from July to October of 1964 by Smith and Reese [153] at latitude +24°. The diameter of the spot was approximately 5,000 km and the rotation period was unusually short -$9^h49^m20^s$, so that in approximately 4 months it accomplished more than three revolutions around Jupiter according to the II system. The relative velocity of the spot was 125 m/sec. Rapidly moving objects with rotation periods from $9^h48^m57^s$ to $9^h49^m18^s$ were previously observed in the zone where the spot was located. In the appearances of these rapidly moving spots Reese and Smith discern the existence of an approximately 12-year periodicity.

A special case is also presented by the Red Spot, whose rotation rate differs from the rate of the II system and does not remain constant so that the longitude of the spot almost continuously, although not monotonically, changes with time.

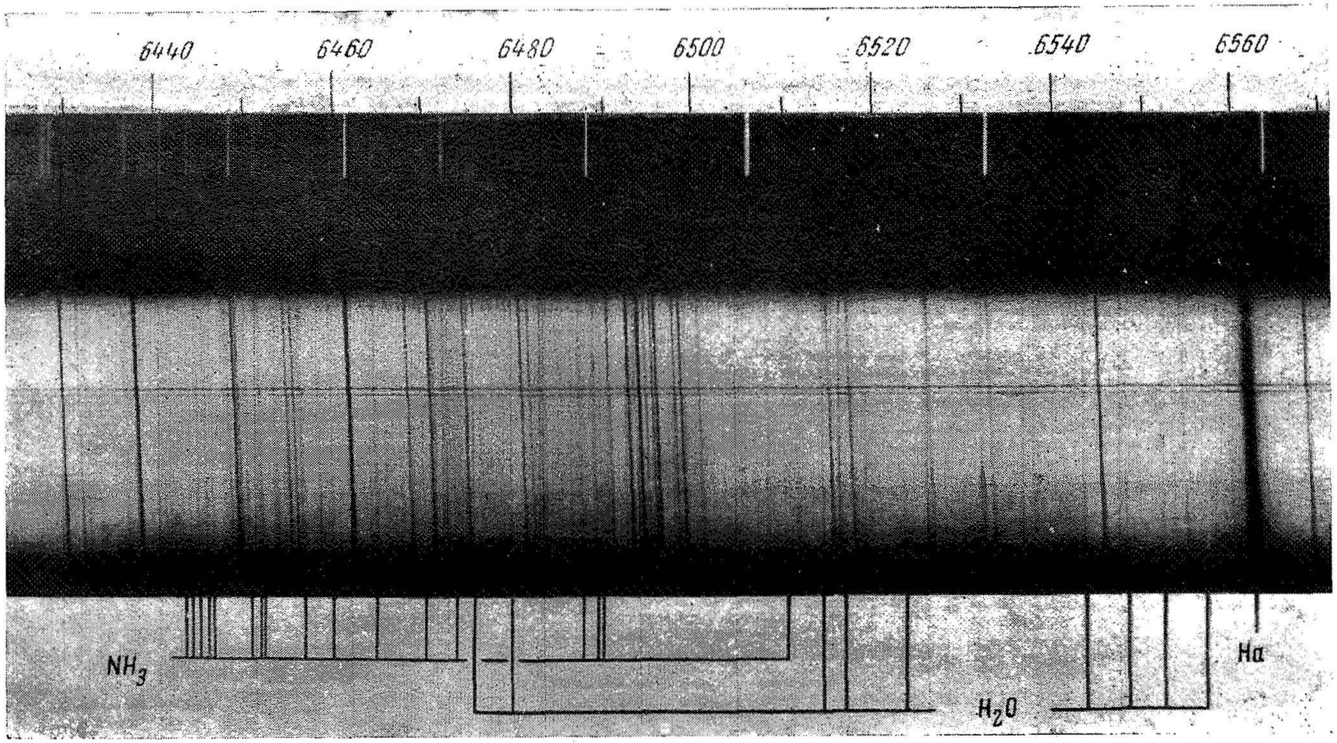


Figure 58. Part of a Spectrogram of Jupiter with High Dispersion (After Giver).

In speaking of the rotation of Jupiter one must remember the results obtained by radio observation methods. The systematic registration of bursts of decameter radio frequency radiation from Jupiter at frequencies of 16-22 MHz has revealed that the bursts repeat periodically, indicating the presence of a local source or of several sources of radio frequency radiation whose rotation period differs from that of the I and II systems. The most uniform statistical analysis of a 10-year period of observations (1950-1960) accomplished by J. Douglas [177], resulted in a rotation period of the radio sources (III system) $P_{III} = 9^h55^m29^s.37 \pm 0^s.16$. This period is close to the II system but is nevertheless somewhat shorter. Longitudes in the III system may be calculated according to a longitude table of the central meridian of the II system by means of the conversion formula

$$L_{III} = L_{II} \pm 0.2742\cdot(JD - 2433339.5), \qquad (5.1)$$

where JD is the Julian date of the moment of observation.

For the present it is not possible to state the atmospheric zone or solid surface of Jupiter to which this rotation system pertains. It is known only that three local sources of sporadic decameter radio frequency radiation exist on Jupiter and that the position of the sources in the III system remains practically fixed. Attempts to identify these with visible details of the cloud cover (with the Red Spot and with bright spots) have proved to be unsuccessful first of all because of differences in the rotation.

b) Spectroscopic determinations of rotation rates. As we already know the linear velocity of rotation on the Jovian equator amounts to approximately 12 km/sec. This value is fully detectable by means of the Doppler effect. By orienting the spectrographic slit along the equator or parallel to the /139
equator at various latitudes we obtain spectrograms in which it is easy to detect the slope of Fraunhofer lines which are lacking on spectrograms taken with a slit orientation along the central meridian. The inclination angle for equatorial spectrograms is [154]:

$$\vartheta_s = \arctan\frac{V_0(1+\cos\alpha)(\cos\beta_\odot + \cos\beta_\oplus)}{\rho r V_s}, \qquad (5.2)$$

where V_0 is the equatorial rotation rate of the planet, α is the phase angle (the angle between the directions from the planet to the sun and to the earth); $\beta_\odot$ and $\beta_\oplus$ are planetocentric latitudes of the sun and the earth; ρ is the width of the spectrogram in mm, determined by the focal distances of the instrument and the spectrograph and by the angular diameter of the planet; rV_s is the radial velocity which corresponds to the Doppler shift on the spectrogram in 1 mm, determined from the known linear dispersion of the spectrograph. For a spectrograph with a dispersion of 30 Å/mm with a Jovian spectrogram width of 4.5 mm and where $\alpha = 0$ (near opposition) $\beta_\odot = \beta_\oplus = 0$, and the Fraunhofer lines will be inclined at an angle $\vartheta_s = 24'.5$, i.e., by almost half a degree. With a spectrograph dispersion of 3 Å/mm the inclination of the lines with the same spectrogram width will equal ~ 4°. Since the lines on the spectrograms are not completely sharp due to the influence of instrumental effects and due to granules of the photo emulsion, it is clear that the accuracy of the determination of this inclination cannot be very high. If we accept that mean error of measurement amounts to approximately 0°.1, accuracy in the determination of rotation rates must be of the order of 0.5-1 km/sec for spectrographs with a dispersion of 10-3 Å/mm and more than 2 km/sec for spectrographs with a dispersion of 30 Å/mm. This means that although the overall rotation rate of Jupiter at the equator may be evaluated by means of spectral observations, the difference of 0.4 km/sec between the I and II systems near the equator is difficult to detect by spectroscopic methods. Spectral determinations of the rotation rate of Jupiter, accomplished at the end of the last century and at the beginning of the present century by A. A. Belopol'skiy [155,156], by J. Kieler [157], and others, although serving to confirm visual observations, were unable to add anything fundamentally new to them. Therefore practically no one attempted any further measurements of the rotation rates of various Jovian zones by the spectral method. Only recently, in 1962, an interesting characteristic of the inclination of planetary absorption lines in the spectra of Jupiter and Saturn was discovered which served as an impetus for new spectrographic observations of the rotation of these planets.

c) Anomalies in the rotation rate of the outer atmosphere ("The Spinrad Effect"). During spectroscopic measurements of the rotation rate of Jupiter usually only Fraunhofer lines (of the solar spectrum) were employed. Absorption lines in molecular bands created by the planetary atmosphere are visible /14 only in spectrograms with high dispersion (not below 5-10 Å/mm). Evaluating the rotation rate by these absorption lines is less convenient since their inclination is two times less than the inclination of the Fraunhofer lines. In fact if the planetary absorption line forms in a layer of atmosphere which reflects solar radiation the angle of inclination of such a line is

$$\vartheta_p = \arctan \frac{V_0(1+\cos\beta_\oplus)}{prV_s}, \qquad (5.3)$$

The inclination is determined only by the motion of planetary points with respect to the earth observer. Therefore, utilizing (5.2), we find that

$$u = \frac{\tan\vartheta_p}{\tan\vartheta_s} = \frac{1+\cos\beta_\oplus}{(1+\cos\alpha)(\cos\beta_\odot+\cos\beta_\oplus)} \geqslant 0.5. \qquad (5.4)$$

Since the angles β and α for Jupiter are always small, the ratio u will always be close to 0.5 (Figure 58).

In 1962 H. Spinrad [158,23] measured the inclination of ammonia lines in the NH_3 band at 6460 Å in spectrograms of the equatorial zone of Jupiter obtained at the Mt. Wilson Observatory in 1934 and at the Mt. Palomar Observatory in 1961 on spectrographs with a dispersion of 5.6 and 3.3 Å/mm, respectively. On the first spectrogram the inclination of NH_3 lines with respect to solar lines was $u_a = 0.23 \pm 0.06$, and on the second spectrogram, the inclination of nine lines was $u_a = 0.34 \pm 0.06$. A spectrogram obtained in 1954 at the Victoria Observatory with a dispersion of 4.2 Å/mm with a slit orientation along the parallel $\phi = \pm 45°$ revealed a line inclination of $u_a = 0.42 \pm 0.05$. Thus the angle of planetary ammonia lines proved to be noticeably less than the anticipated value $u = 0.5$.

The anomaly of line inclination discovered by Spinrad received the name "The Spinrad Effect." What does this effect indicate? If the line inclination observed is caused exclusively by Doppler shift then this means that the atmospheric layers of Jupiter in which the formation of ammonia lines occur rotate more slowly than those layers which reflect the suns rays. Since the effective reflection of solar radiation is developed mainly by the surface of the Jovian cloud layer while molecular absorption is at least partially generated in the outer atmosphere, it may be assumed that the outer atmosphere itself rotates more slowly. Where $u_a = 0.24$ ammonia in the outer atmosphere does not rotate at a rate of 12 km/sec, but at approximately 6 km/sec, or, in other words, in the outer atmosphere gas masses are displaced with velocity $V \leqslant 6$ km/sec from the west to the east--in the direction opposite to the direction of planetary rotation.

It would seem natural that the same unusual inclination would also be detected in the methane line. But CH_4 lines in the band at λ 6190 Å are very weak so that there were no satisfactory results in this area. For a spectrogram obtained in 1961 Spinrad and Trafton found an inclination in CH_4 lines $u_m = 0.39 \pm 0.06$, but without any particular confidence in the reliability of the measurements. /142

The discovery of Spinrad generated a great deal of interest, but practically all subsequent attempts to detect anomalies in NH_3 line inclination were unsuccessful.

In three spectrograms of Jupiter obtained in 1963 with a dispersion of 4 Å/mm in NH_3 lines, C. Fehrenbach and P. Guerin [159] determined the inclination as $u_a = 0.492$. L. Giver [160], in accordance with spectrograms from 1963 with a dispersion of 8 and 2 Å/mm obtained NH_3 line inclination of not less than 0.485. A negative result was also obtained by W. Sargent and R. Catchpole [161] from 3 spectrograms made in 1962 and by Spinrad and Giver [162] from 2 spectrograms made in 1964 and 1965. The latter authors also refer to a private communication from G. Münch who obtained a value of $u_a = 0.485$ from a series of spectrograms in 1963.

A single instance of a small decrease in the inclination of ammonia lines was detected in 1963 by M. Nishida and J. Jugaku [163]. In spectrograms with a dispersion of 2.9 Å/mm, obtained on November 23, 1963, the value obtained for 5 lines proved to be $u_a = 0.412 \pm 0.024$.

Of course the observations listed are clearly not sufficient in order to come to completely definite conclusions concerning the reality and the causes of the "Spinrad effect." If this phenomenon is real then it must be considered as variable with time and certainly not a frequent phenomenon.

The presence in the outer atmosphere of Jupiter of strong zonal winds is quite possible. T. Owen and D. Staley [164] have directed attention to the recent discovery of the alternation of eastern and western currents in the Earth's stratosphere above the equator (see, for example [166], pp. 152-153). The period between two successive maximums in velocity amounts to approximately 26 months. In an analogy with the Earth, on Jupiter we can also expect that in the outer atmosphere atmospheric currents exist which are variable in direction; in connection with the movement of these currents from the west to the east the wind speed in relation to the cloud layer may reach values of 6-7 km/sec. Assuming just as on the Earth that the periodicity of the stratospheric currents is associated with solar activity, Owen and Staley predicted that the next anomaly in NH_3 line inclination would be observed in the fall of 1963, which was observed by Nishida and Jugaku.

It would be tempting to consider such a coincidence as a confirmation of the reality of the "Spinrad effect." But nevertheless a certain amount of care is necessary since all of the observations are sporadic in nature. It is absolutely necessary to conduct a systematic study of this effect at two or more observatories simultaneously. /14

d) **Possible causes of anomalies in line inclination.** The interpretation of the "Spinrad effect" by Doppler line shift as a result of a shift in gas masses in the outer atmosphere is not particularly convincing. It is known that in the outer atmosphere ammonia is more intensively concentrated with depth in proportion to proximity to the cloud surface. This means that the effective absorbent layer for weak NH_3 lines must be situated near the Jovian cloud layer. On the other hand ammonia also absorbs light and creates planetary spectrum lines in the same cloud layer. But within the cloud layer ammonia certainly cannot shift with a velocity which differs from the velocity of the cloud particles reflecting solar radiation. This means that the ammonia lines which form in the cloud layer must display a normal inclination $u_A = 0.5$. If gas masses in the outer atmosphere are in motion with respect to the clouds we must observe splitting or noticeable diffusion of ammonia lines with proximity to the edge of the disk (Figure 59).

The diffusion of ammonia lines probably would be observed even if absorption in the cloud layer did not occur, since it is difficult to assume the absence near the cloud layer of a zone of gradual reduction in wind velocity in the outer atmosphere. A sharp drop in velocity would lead to the formation of vortexes and to the generation of powerful, turbulent motion in the cloud layer, i.e., in the final analysis the relative wind velocity would be small near the cloud surface itself. Since the maximum ammonia concentration must occur on this exact level the effective NH_3 absorption here would be sufficiently high to lead to the formation of absorption lines with an almost normal inclination.

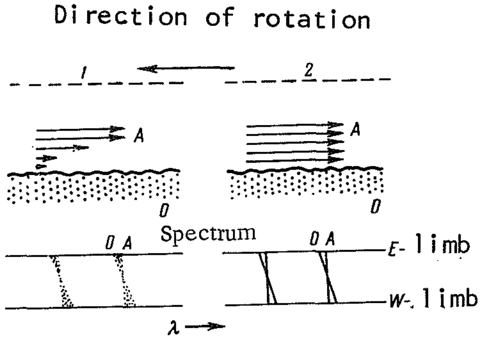


Figure 59. Splitting or Broadening of Ammonia Lines Near the Edge of the Jovian Disk, Which Must be Observed with Different Rotation Rates for the Outer Atmosphere (A) and the Cloud Layer (O).

Another explanation was proposed by Öpik [165]. He believes that near the center of the disk the NH_3 lines must be shifted toward the longer wavelengths due to the influence of pressure. Near the center of the disk a ray of light must penetrate to a great depth in the planetary atmosphere, and therefore the effective level of the formation of absorption lines will be located at a greater /144 depth. Since the pressure increases with depth the position of the center of the absorption line will depend on pressure P at the corresponding level

$$\frac{\nu_e - \nu_c}{\alpha_e} = A\left(\frac{P_c}{P_e} - 1\right), \qquad (5.5)$$

where ν_c is the frequency of the line center at pressure P_c, ν_e is the same at pressure P_e, α_e is the line half-width at $P = P_e$, $A = 0.725$. If near the edges of the disk absorption lines are generated at the effective level with $P_e < P_c$ (we may disregard the difference in level temperatures), then $\nu_e - \nu_c > 0$, i.e., near the center of the disk the line must be displaced toward the lower frequencies--toward the red part of the spectrum. This displacement will be noticeable only if $\nu_e - \nu_c > 2\alpha_e$, but then $A\ (P_c/P_e - 1) > 2$ or $P_c/P_e > 3.8$ must obtain. The pressure at the effective level near the center of the disk must be almost four times greater than at the effective level of the formation of lines near the edges of the disk. For weak, unsaturated ammonia lines such a phenomenon is of low probability if they are basically formed in the outer atmosphere. The main point, however, is the fact that the pressure effect described must appear symmetrically for both edges of the disk, i.e., the lines will not appear to be inclined, turned by the prominance in the center of the disk toward the red end of the spectrum. Giver [160] did not detect curved lines on spectrograms from the Lick Observatory which encompassed the entire diameter of the Jovian disk. A very weak NH_3 line prominance might have been noted but this was toward the violet end of the spectrum.

For the present we must state that the "Spinrad effect" as obtained is neither decisive observational confirmation nor satisfactory explanation. In fact this effect may be variable with time like the phenomenon of the increase in temperature in the shadow zone of the Jovian satellites. Some observers are even inclined to associate these two phenomena with one another.

§2. The Formation of Cloud Belts and the Causes of Equatorial Acceleration

a) The overall conditions of atmospheric circulation on Jupiter. While the basic characteristics of the Jovian atmosphere are unknown, including the extent of the atmosphere in altitude, the distribution by altitude of the main physical parameters, and the main point, i.e., the sources of energy which cause the processes observed in the atmosphere, it is impossible to develop a theory for the atmospheric circulation of this planet. It is impossible /145 to carry over mechanically into the atmosphere of Jupiter the results of theoretical calculations of the overall circulation of the Earth's atmosphere or of hydrodynamic concepts concerning the rotation of the sun.

The basic cause for the generation of large-scale horizontal and vertical shifts in atmospheric masses on the planet is the difference in pressure and temperature at different altitude, latitude and longitude levels. However the velocity and direction of these shifts, which determine the nature of atmospheric circulation, still depend on a number of other factors including in particular the velocity of the axial rotation of the planet, on atmospheric viscosity, on properties "underlying" the surface, etc.

On planets of the Earth group the basic source of energy for atmospheric circulation is solar radiation, which leads to heating of the surface and the atmosphere of the planet. At the equatorial zone planets are heated to a greater degree, i.e., due to the difference in illumination the quantity of heat which impinges upon the planet is not identical at the equator and at the poles. Therefore a temperature and pressure gradient must exist in the planetary atmosphere, directed along the vertical and from the equator to the poles.

Correspondingly atmospheric masses at the equator must flow upward at all longitudes and in high-altitude layers must shift toward the poles. At the poles, where heat losses as a result of atmospheric radiation are greater than the current from the sun, incoming masses of heated air make up for this loss and then, descending to a lower level, return to the equator. Since the planet rotates, as a result of Coriolis acceleration a zonal acceleration component of atmospheric mass shifts appears which increases with altitude and coincides in direction with the direction of planetary rotation. Therefore gas masses are shifted toward the poles and back again not along the meridian but along a spiral with respect to the planetary surface. Such an atmospheric circulation cycle is called a symmetrical one.

If atmospheric heating at the equator is sufficiently great a symmetrical circulation cycle transformed into a wave cycle [169]. Here horizontal heat transfer in the atmosphere occurs by means of the wave displacement of cold and heated masses in parallel to the planetary surface (Figure 60).

The rotational axis of many planets is inclined to the orbital plane. In /146 this case the cycle of planetary irradiation by solar radiation must undergo noticeable seasonal fluctuations, which is reflected in the nature of the transfer of heat energy in the northern and southern hemispheres of the planet. The inclination of the rotational axis of Jupiter (~3° from the normal to the plane of the ecliptic) is too small to influence annual circulation processes in the atmosphere. Therefore in the absence of the effects of other factors, meridional transfer into the Jovian atmosphere must be stable.

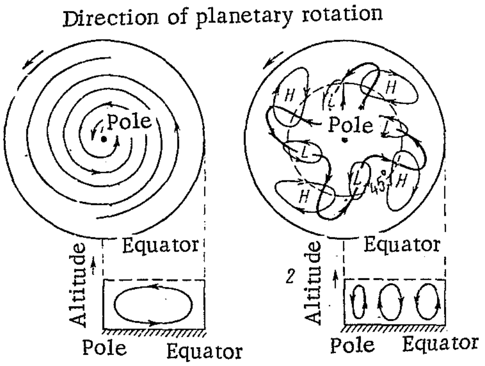


Figure 60. Symmetrical (1) and Wave (2) Cycles of Planetary Atmospheric Circulation (After Mintz). Heavy line--currents in the upper layers of the atmosphere; Fine lines--currents in the lower layers; H, high-pressure region; L, low-pressure region.

Acceleration which is effective during the development of the meridional pressure gradient $\Delta P/\Delta\phi$ equals

$$G = \frac{\Delta P}{\rho r \Delta\varphi}, \tag{5.6}$$

where ρ is density, r is the planetary radius. Since Jupiter rotates very rapidly around its axis, regular shifts in its atmospheric masses may not occur strictly along the meridian due to the appearance of the velocity component directed parallel to the equator and linked with the necessity of maintaining angular momentum. During the shift of a certain point with latitude ϕ to latitude ϕ' this zonal component will equal [167]:

$$u = r\omega \frac{\cos^2\varphi' - \cos^2\varphi}{\cos\varphi}, \tag{5.7}$$

where ω is the angular velocity of planetary rotation. The meridional motion of gas masses which develop due to the presence of the pressure gradient will be opposed by a force which acts in the opposite direction (Coriolis force) [168]. Its acceleration equals:

$$A = 2\omega u \sin\varphi = 2r\omega^2 \frac{\cos^2\varphi' - \cos^2\varphi}{\cos\varphi'} \sin\overline{\varphi}. \tag{5.8}$$

Meridional currents may be maintained on Jupiter only if $G \geqslant A$, i.e.,

$$\frac{\Delta P}{\rho r\omega\varphi} > 2r\omega^2 \frac{\cos^2\varphi' - \cos^2\varphi}{\cos\varphi'} \sin\overline{\varphi}. \tag{5.9}$$

If circulation on Jupiter is maintained only as a result of heating by solar radiation and with temperature at the equator $T_0 = 160°K$ and at latitude $\phi = 45°$, we obtain $T \simeq T_0 \sqrt[4]{\cos \phi} = 0.92\ T_0 = 147°K$, $\Delta P \simeq 0.048$ atm, from which $\Delta P/\Delta\phi \simeq 0.064$ atm/rad $\simeq$ 0.001 atm/degree of latitude. This means that on Jupiter the inequality (5.9) may be fulfilled only near the equator /147 (where $\sin \bar{\phi}$ is small) and within the limits of very small latitude intervals, when the difference $\cos^2\phi' - \cos^2\phi$ is small. Meridional currents even within the limits of a zone 10-20° of latitude in width cannot exist on Jupiter. In fact the meridional displacements of even individual small details of the cloud layer are rarely observed on Jupiter. But if the horizontal pressure gradient is linked with temperature differences caused by heating of atmosphere by internal heat sources, the magnitude of this gradient may in certain cases prove to be significantly large and sufficient for a substantial transfer of atmospheric masses in the meridional direction. This may lead to sharp disruptions in the usual zonal distribution of cloud belts, which in fact has been observed on Jupiter during several years, although rarely.

If we judge by the ordinary distribution of cloud belts in which sharp differences in breadth and latitude at various longitudes are lacking, it is possible to believe that the nature of circulation in the Jovian atmosphere must approach the symmetrical rather than the wave cycle. But we cannot consider it completely coincidental with the symmetrical cycle since we do not observe the continuous transfer of atmospheric masses to the poles or to the equator. Individual zones and bands within specific limits may be described as relatively stable formations which form a basis for assumptions that they represent vortex rings which surround the planet. The possibility of the existence of such atmospheric rings was shown by Helmholtz. If friction is completely absent in a liquid or in a gas such vortex rings would remain stable during the course of a long period of time. However viscosity of the medium and turbulent friction lead, naturally, to the fact that part of the rotational energy is expended on overcoming friction and therefore without the addition of supplementary quantities of energy the vortex rings could not exist long in a planetary atmosphere.

b) The sources of the formation of dark bands. The relative depth of the Jovian atmosphere from the level of the solid or semi-liquid surface of the planet to the upper limit of the cloud layer more than likely amounts to not more than 1-2% of the planetary radius. The width of the majority of dark bands equals several thousands of kilometers but the equatorial bands attain widths of 15,000 km and greater.

Therefore the horizontal extent of the bands in latitude significantly exceed the vertical depth of the cloud-gaseous atmosphere.

It is apparently necessary to speak of the formation of dark belts in the Jovian cloud layer, while considering that the bright zones reflect the normal, "non-turbulent" state of the cloud cover. It is true that if we also consider /148 the polar region, the relative fraction of dark matter on the visible surface of Jupiter may even exceed the fraction of bright matter, so that the problem of the striped structure of the Jovian disk would resemble the problem of the coloring of a zebra where it is not clear whether dark bands are on a bright background or vice versa. Nevertheless in the case of Jupiter it is possible to give a more definite answer since the dark bands, as a rule, are characterized by a more active and clearly expressed turbulent structure than the zones. The micro-turbulent structure of the Jovian cloud belts has unfortunately not been studied at all, although it may be in this structure that a clue to the reasons for the mechanism of band formation will be found. Visual observations in this problem are not to be trusted since almost simultaneous drawings and excellent descriptions of the processes observed in the development of individual centers of turbulence and cloud details differ very greatly among different observers. Photographs give us objective information but the resolution of photographs is limited to a greater degree than the visual method by the condition of the Earth's atmosphere. High-quality photographs of Jupiter with high resolution are too rare in order to make possible the study of short-term processes. Now this problem for photographic observations has been placed in a program of international cooperation in the study of Jupiter.

For the present it is possible to speak only of large-scale processes. But even here a great deal is still not clear. The main problem which still has to be answered before we can develop a dynamic model of the Jovian atmosphere consists of the factors which cause the appearance of the dark substance on the Jovian surface. If we assume that this is associated with vertical currents from deep layers of the atmosphere then it is necessary to search for a local atmospheric heating mechanism which must depend on internal processes on the planet since heating by solar radiation may influence only the external layers of the atmosphere.

We shall assume that a heat source is located on the solid Jovian surface which has limited dimensions in latitude and longitude. Near the planetary surface the atmosphere has temperature T'_0, and above the surface of the heat source, the temperature is $T_0 > T'_0$. If a gas mass rising above the source has the same chemical composition as the surrounding atmosphere and the ascent occurs adiabatically, then the temperature gradient for both the surrounding atmosphere and for the ascending gas mass will be identical and will be equal to the adiabatic gradient. Then at altitude h

$$\begin{aligned} T' &= T_0' - \Gamma_a h, \\ T &= T_0 - \Gamma_a h. \end{aligned} \qquad (5.10)$$

The velocity of the progress of the heated gas mass in the absence of friction is /149

$$V^2 = 2gh\,\frac{T_0 - T_0'}{T_0'}. \qquad (5.11)$$

E. Schoenberg [170] accepting $T'_0 = 300°K$, $T_0 = 500°K$ and $\Gamma_a = 6.8$ and 10 deg/km, obtained an ascent velocity where h = 20 km from 580 to 730 m/sec. When gas friction is considered the velocity is less and amounts to 157-200 m/sec. These values proved to be several times more than the velocity of ascending currents in the Earth's atmosphere (up to 40 m/sec in cumulus congestus). Of course here it is possible to speak only of the order of magnitude of velocity since the initial data are extremely conditional. Thus the adiabatic gradient in the Jovian atmosphere apparently does not exceed 4 deg/km, but the difference in temperatures at the surface of the planet may be considerably below 200°, although the temperature of the surface itself may also be considerably above 300°K. The altitude of 20 km from the surface of the planet to the upper limit of the cloud cover, accepted by Schoenberg, is quite arbitrary. But in any case it is possible to assume that the rate of ascent of the heated gas amounts to several tens of m/sec. Such vertically ascending gas masses in view of the preservation of the rotational moment will be deflected to the west (descending colder gas will be deflected to the east of the vertical).

Longitudinal deviation may be found from the equation

$$\frac{d\lambda}{dt} = \frac{2h}{r}\omega, \tag{5.12}$$

where h is the altitude; r is the planetary radius; ω is the angular velocity of rotation. If ω = 870 deg/day, then

$$\lambda - \lambda_0 = -\frac{2h}{r}\frac{870}{86400}(t - t_0). \tag{5.13}$$

We shall assume altitude h = 250 km and the mean ascent velocity V = 50 m/sec. Then during time of ascent $t - t_0$ = 5,000 sec the gas mass will be deflected toward the west by $\lambda - \lambda_0 \simeq 0°.36$. It is clear that even during fluctuations in ascent of velocity as a result of a changing difference in the temperatures of the source and the surrounding surface, the longitudinal deviation of the ascending mass will not exceed 1°, i.e., explaining the formation of dark bands simply by the deviation from the vertical of ascending currents is not possible.

The appearance itself of dark matter on the surface of the cloud layer has so far not been explained. Several versions are possible here. The dark matter may develop during temperature changes from the bright matter when the ascending gas currents reach the cloud surface. The dark matter may emerge from deeper layers where it exists continuously (V. G. Fesenkov [142]). The dark substance may be thrown off from the depths of the planet during volcanic inversions and may be similar to terrestrial volcanic ash (S. K. Vsekhsvyatskiy [171-173]). /150

Nevertheless the convection mechanism for the formation of dark cloud belts and spots is the most probable. It is possible, for example, to assume that although the interior of Jupiter is heated more or less uniformly than the limits of concentric zones, the Jovian mantle or a transition layer between the mantle and the atmosphere has, in different latitudinal belts, non-identical thermal conductivity. Since the pressure on the surface of the solid planet or of the transition layer amounts to 10^4-10^5 atm, it is possible that the transition layer matter under the influence of particular causes, for example, tidal disturbances, may change its phase and correspondingly its thermal conductivity. Then the release of heat would be greater where the thermal conductivity is lower or perhaps the depth of the transition layer in different planetary belts is simply not identical, which would cause the non-uniform release of thermal energy. The position of such zonal heat sources may change, for example, under the influence of tidal forces arising from Jovian satellites.

The hypothesis of active volcanism on Jupiter, advanced by S. K. Vsekhsvyatskiy, may explain several phenomena on Jupiter of an eruptive nature (the appearance of short-term bright and dark spots, bursts of radio frequency radiation in the decameter range). However, the Red Spot or the extended existence of cloud belts can hardly be considered as the result of volcanic processes. The sources of these formations have been maintained for a long time, although a certain instability in the release of energy does occur. It is not clear whether disintegration of the solid mantle occurs on Jupiter over huge expanses, that is over a distance of tens of thousands of kilometers. It is necessary to investigate very carefully the energy of phenomena which occur on Jupiter. However it is necessary to study these phenomena from a quantitative point of view which has not so far been accomplished.

c) Equatorial acceleration. The acceleration of rotation in the equatorial region is observed not only for Jupiter and Saturn, but for the sun as well. Several different explanations for the equatorial acceleration of the sun have been proposed, however these cannot be applied to Jupiter because of the different nature of the phenomenon. On the sun a reduction in the angular velocity of rotation occurs gradually from the equator toward the poles, while on Jupiter a sharp transition from one rotational velocity to another is observed.

With the exception of the work by E. Schoenberg [170] until the present time there has been no satisfactory explanation of the equatorial acceleration of Jupiter, although such attempts have been made repeatedly. Schoenberg proceeded from the assumption that the dark equatorial bands are formed as a result of the progress of heated gas from the depths of the atmosphere or /151 even as a result of matter thrown off in the NEB and SEB from the interior of Jupiter. The ascending masses of matter at latitudes of approximately 10-12° attract neighboring gas masses while developing a certain atmospheric rarification and therefore a horizontal pressure gradient from the equator to these latitudes. In the presence of a horizontal pressure gradient a meridional gas shift begins in the lower atmospheric layers from the equator in the direction of the poles with ascending currents (Figure 61). An inverse gas shift must occur in the upper atmospheric layers so that meridional circulation develops.

On a rotating planet such circulation cannot be maintained due to the effect of Coriolis force. Therefore a gas mass which is in motion in the lower atmosphere from the equator to latitudes ~ 8°, where the gas ascent occurs, is deflected in the direction of planetary rotation. If frictional forces are not considered the longitudinal component of atmospheric currents generated in this case near latitude 8° will reach 360 m/sec, according to Schoenberg's calculations. After the ascent any particle of the gas mass will already be in motion toward the equator, but not along the meridian, but with a certain displacement in the direction of rotation. The velocity and exact direction of this displacement is difficult to calculate since it is difficult to determine the value of the meridional pressure gradient in the upper atmospheric layers. In one way or another any gas particle in the zone between the equator and latitude 8° will move in a spiral. Here friction will play an important role and therefore Schoenberg accomplished his calculations with consideration for friction, having obtained agreement of the calculated longitudinal velocity component with the mean observed value 115 m/sec with respect to the II rotational system.

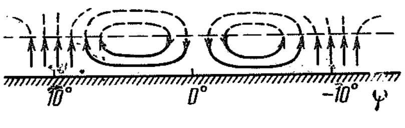


Figure 61. Possible Diagram of Jovian Atmospheric Circulation in the Region of the Equator and the Equatorial Bands.

In Schoenberg's calculations, of course, there are a number of arbitrary assumptions with respect to atmospheric depth, mass, and the velocity and quantity of gas absorbable during the ascent of matter in the NEB and SEB. The mechanism of the displacement of Jovian cloud masses at higher latitudes remains unclear. Based on Schoenberg's hypothesis similar acceleration effects must also occur in other bright zones, at least in the temperate latitudes. The ascending gas masses in the temperate belts must develop a pres- /152
sure gradient in adjacent atmospheric zones. Then we would observe various rotation rates depending on the velocity of the ascent of the heated gas in one band or another.

In the equatorial zone we would also observe different rotation rates during different years. In fact, the intensity of the NEB and SEB fluctuate remarkably from year to year. When in 1962 the equatorial zone was concealed by the north and south belts, which merged in one wide band, we could have anticipated significant anomalies in the rotation rate of the equatorial belt of Jupiter. However this was not registered.

In his calculations Schoenberg accepts the elevated altitude of the gas masses as 10-15 km. This value is apparently too low. If the source of heat or of matter thrown off is located on the solid surface of the planet then the ascending gas must cross the thickness of the atmosphere of at least several hundred kilometers. Therefore Schoenberg's numerical results may be considered as illustrative only. However it is interesting to note that even at a low ascent altitude, the energy which must be imparted to the atmospheric masses in order to provide for the equatorial acceleration observed amounts for each 1 g of mass to approximately $2.8 \cdot 10^8$ erg/min. From the sun alone 1 g of Jovian atmosphere with an albedo of 0.44 receives 10^4-10^5 erg/min, depending on the thickness and average density of the atmosphere assumed.

§3. The Red Spot--Dynamic Characteristics

a) Displacements in longitudes. Numerous observations of the Red Spot have revealed that it is always located at practically the same latitude; the center of the Spot has a latitude of 22°.5, and deviations from this value do not exceed 1-1°.5. Even these small shifts of the Spot in latitude are probably not real and may be associated with the fact that overlying clouds sometimes appear either on the north or on the south edge of the Spot which leads to an apparent displacement of its center.

The longitude of the Red Spot is another matter entirely. While falling under the II rotational system, the Spot in its motion either leads this system, i.e., it decreases its longitude, or as can be seen from Figure 62, sometimes begins to drop behind somewhat (the longitude is increased). During the period from 1840 to 1880 the longitude of the Spot more or less uniformly decreased, then its accelerated motion with respect to the II system was replaced by retarded motion in the period from 1886 to 1910. Then acceleration /153
in the longitudinal motion of the Spot was again observed, which in 1930 was in turn replaced by retarded motion. During the period from 1844 to 1957 the Red Spot made approximately eight additional revolutions around Jupiter in comparison with the II system.

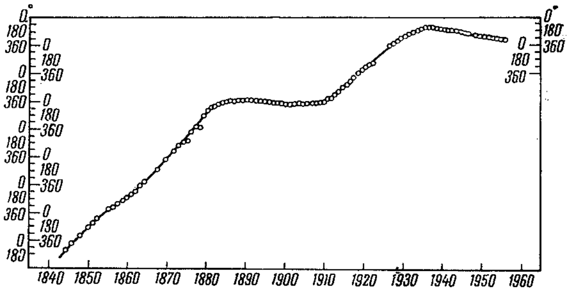


Figure 62. Changes in the Longitude of the Red Spot (After Loebering).

The rotation period of the Red Spot (Figure 63) underwent changes from $9^h55^m32^s$ to $9^h55^m44^s$. We are reminded that the period of the II system amounts to $9^h55^m40^s.6$. In certain years rapid changes in the rotation period of the Spot were observed; a sharp acceleration in Spot motion 1860, 1910, 1922 and 1938, a sharp retardation in 1880, 1920, 1925 and 1942. In recent years (1962-1963, 1964-1965) a slow increase in the longitude of the Red Spot has been observed; the rotation period still remains greater than the period of the II system.

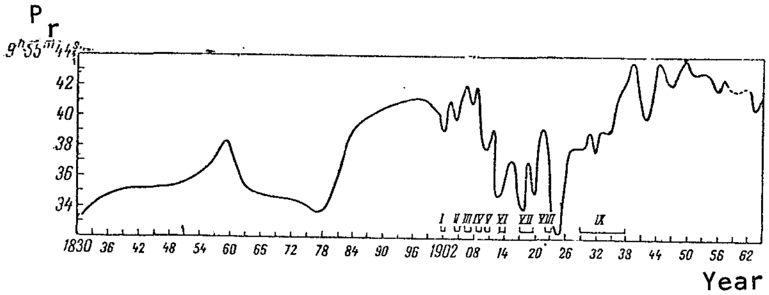


Figure 63. Changes in the Rotation Periods of the Red Spot. The Roman numerals designate periods of conjunction of the Spot and the South Tropical Disturbance.

In analyzing the change in the rotation period (P_r) of the Red Spot during the period 1831-1955, Lenham [175] came to the conclusion that the overall century-long motion P_r could be represented by the rectilinear function

$$P_{ra} = 9^h55^m34^s{,}42 + 0^s{,}058\,(t - t_0), \tag{5.14}$$

where t is in years; t_0 = 1830. Fluctuations in the value P_r, which have a clearly periodic nature, are superimposed on this line. It is not possible to determine the exact value of this period of fluctuation but best agreement with observations is obtained for a period of 50 years, so that deviations from the rectilinear function are satisfactorily represented by the curve

$$\Delta P_r = 2{,}75 \sin \frac{2\pi\,(t - t_0)}{50} - 0{,}85, \tag{5.15}$$

where ΔP_r is in sec; t_0 = 1885.0; t is in years.

Corresponding deviations in the position of the Red Spot from those calculated in accordance with (5.14) in fractions of the circumference of the planet are shown below.

If P_{ra} is considered to be the rotation period of the solid body of Jupiter, then it is apparent from the data cited below that the position of the Red Spot cannot in any way be associated with any constant segment of the planetary surface. By accepting any other rotation period of the solid body, also uniformly changing with time, we only increase the difference obtained between the position of the Spot and a point invariably associated with the solid surface. However as we see below if the conditions of uniform or uniformly retarded rotation of the solid body are not limited then it is possible to examine the Red Spot as a formation associated with the solid surface: /154

Interval, Years	Longitudinal Displacement in Fractions of the Planetary Circumference	Interval, Years	Longitudinal Displacement in Fractions of the Planetary Circumference
1831,50—1849,25	—0,30	1861,25—1881,10	—1,59
1849,25—1851,00	+0,01	1881,10—1909,50	+1,94
1851,00—1853,25	—0,02	1909,50—1935,90	—1,92
1853,25—1861,25	+0,24	1935,90—1955,60	+0,70

Tr. Note - Commas indicate decimal points.

Lenham also noted the presence of a relationship between the roatation period of the Spot and its latitude. Although as noted above the latitude of the Spot remains almost fixed and has not been very accurately determined, nevertheless it seems that the correlation coefficient between the rotation period and the length of the Jovian circumference at the parallel of the Red Spot equals 0.672. A certain decrease in the latitude of the Spot corresponds to an increase in the rotation period. Perhaps this is not directly connected with the latitudinal shift of the Spot. According to photographic observations in 1962-1965 (152 photographs) E. Reese and H. Solberg [176] found that latitudinal fluctuation in the center of the Spot correlates with its latitude--the correlation coefficient equals 0.66. Here the change in the width of the /155
Red Spot was caused mainly by large latitudinal fluctuations in the southern edge of the Spot in comparison with the north edge. The relationship between the rotation period and latitude, just as between the length of the Spot and longitude and between the length of the Spot and latitude was not detected.

b) Interaction with other cloud formations. First of all the interaction of the Red Spot with the southern component of the south equatorial belt and the south temperate belt attracts attention. A depression is almost always formed in the SEB_s--the "Red Spot Hollow," so that although the Spot is submerged in the belt, it does not come into contact with the belt. A bright interval is located between the Spot and the belt. The impression is created that an atmospheric current from the north envelops the Red Spot and squeezes the edge of the SEB to the north while creating a recess in this belt. A completely different picture is observed at the location of contact between the Spot and the STB. In fact the south temperate belt reacts not at all to the presence of the Red Spot, touching or even overlapping the Spot with its southern edge. The diverting effect of the Red Spot on the southern component of the SEB is maintained even when the Spot itself is not visible.

The relative velocity of the motion of the cloud and gas masses flowing around the Red Spot amounts on the average to approximately 2 m/sec. This is an extremely low velocity if we remember that the difference in the velocities of the equatorial currents at the border between the I and II systems exceeds 100 m/sec.

Recently at the Observatory of the University of New Mexico E. Reese and B. Smith [214], on the basis of a vast amount of photographic material, investigated several small dark spots in the southern component of the south equatorial belt and on the northern edge of the south temperate belt during passage of these spots near the limits of the Red Spot. An analysis of the observations permitted these investigators to establish that the Red Spot, or at least its peripheral zone, possesses an inherent circular motion, counter-clockwise in direction. The period of circulation of the matter in the Spot is approximately 12 days and the velocity of motion at the northern and southern edges of the Spot is 255 km/hr, and on the eastern and western edges, approximately 70 km/hr.

A most interesting phenomenon occurred when the Red Spot entered into conjunction with the south tropical disturbance--an active region situated between the SEB and the STB in the south tropical zone. This active region, consisting of a dark substance with multiple bright spots, had a rotation period shorter than the Red Spot. The length of the disturbance in longitude during its appearance in 1901 equaled several degrees, but subsequently it became elongated in longitude so that in 1918-1919 the maximum length reached 190° and in 1935, 230° or almost two-thirds of the circumference of the south tropical zone. Correspondingly the rotation period of the south tropical zone /156 also increased; if in 1902 the difference in the periods of the Red Spot and the disturbance during their first conjunction amounted to 23 sec, then during their ninth conjunction in 1929-1935 the difference did not exceed 6 sec.

During the approach to the Red Spot Hollow in 1902 (the Spot itself at this time was not visible) the southern tropical disturbance did not fill the hollow, but having divided itself into two currents, flowed around it from the north and the south so that while it was passing through the longitude of the Red Spot (approximately six weeks) a bright oval was visible on the background of the gray substance of the disturbance at the location where the Spot must have been located. During conjunctions with the disturbance (except the most recent, the ninth) the Red Spot revealed a tendency toward accelerated rotation; its period became shorter. The edge regions of the disturbance during the approach to the Spot accelerated its motion so that the region of the Spot (or its hollow) was traversed by the edges of the disturbance with a velocity exceeding by approximately 10 times the normal velocity of the disturbance; after transversing the Spot, the velocity of the disturbance was again reduced.

At the present time it is difficult to furnish a firm interpretation of the phenomena observed in the region of the Red Spot. It is clear only that this formation or its source on the surface of Jupiter causes a significant perturbation effect on the dynamic processes in the atmospheric region adjacent to the Spot. Changes brought about by the Spot in the state of the atmospheric conditions apparently have their origin in the interior layers and reach the visible surface of the cloud layer. However, as shown by several observers, a specific level exists in the outer atmosphere above which the perturbation effect of the Spot is not propagated. Occasionally the passage of cloud details above the Spot has been noted. Thus in 1952 Loebering [178] noted that the southern part of the Red Spot was partially screened by a small cloud tongue, which was extended from the south temperate belt. In 1966 and 1967, as shown by photographs obtained at the Astrophysics Institute of the Academy of Sciences of the Kazakh SSR, part of the Red Spot was screened by cloud matter and the Spot was deprived of the many sharp details which it possessed in 1964-1965.

The shape of the Red Spot itself, as might be expected, to a significant degree reflects the nature of its interaction with the surrounding gaseous medium, or is the result of interaction with the atmospheric source of the formation of the Spot, which may be located on the solid surface of the planet. It is especially important to direct attention toward the spindle-shaped outlines of the eastern and the western edges of the Spot, which are reminiscent of the contour lines of current in a liquid, surrounded by a solid annular or oval body (Figure 64). Since the atmospheric depth under any assumptions is obtained as at least one order of magnitude less than the length of the Spot it is quite possible that the disturbance, created in the /157 atmosphere near the surface of the planet, may reach a cloud layer without essential changes. The relative velocity of streamlined flow is small and therefore a noticeable vortex trail does not form behind the streamlined body.

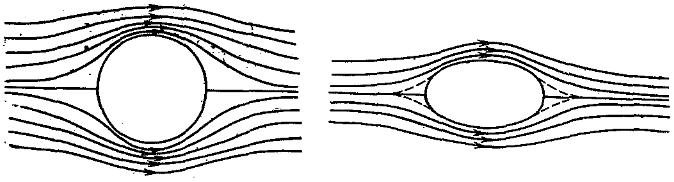


Figure 64. Lines of Current During Flow Around Bodies of Round and Oval Shape.

Photographs and visual observations reveal that coloring of the Spot near the edges is somewhat different in comparison with the central region; ordinarily the edges seem to be darker. This darkening may be associated either with rotational motion within the Spot, accelerating matter toward the periphery, or with a certain temperature gradient near the edges which develop a temperature cycle different from that in the center in the edge zones and correspondingly a change in substance coloration. A detailed photometric investigation of the Spot from large scale photographs with good resolution would be useful both for the investigation of motion within the Spot, as well as for the study of the velocities of other cloud details which pass near the Spot.

§4. Hypotheses Concerning the Origin of the Red Spot

a) The hypotheses of the "floating island." In recent years two alternative hypotheses have been seriously discussed; these include the hypothesis of the "floating island," which has undergone several modifications, and the hypothesis of the "gas column," which links the Red Spot with a specific region on the solid surface of the planet. The old concepts to the effect that the Spot represented a lake of molten matter or the result of a powerful volcanic eruption were based on the assumption that the surface of Jupiter has a very high temperature.

The volcanic hypothesis was abandoned for the reason that displacement of the Red Spot in longitude seemed to contradict its link with any kind of formation on the solid surface of Jupiter. In 1892 J. Hogue expressed for /15 the first time the idea that the Red Spot might be a body floating in a liquid or in a plastic medium with a density of approximately 0.5. In 1939 R. Wildt advanced the hypothesis that the Spot represented a large solid body, the length and width of which approximately corresponded to the dimensions of the visible oval of the Spot and with a depth corresponding in order of magnitude with the width. This body swims in an ocean of heavily compressed gas. The hypothesis of Wildt was developed by B. Peek, who suggested [102] a two-phase model of the floating body. According to Peek, the substance or at least one of the substances, making up the body must be capable of existing in two solid phases which differ in density. The denser phase must correspond to the lower part of the body located at levels of higher pressure of the surrounding atmospheric ocean. The body floats so that the phase interface is located at a level corresponding to the critical pressure for the phase transition. Depending on the relative quantity of the substance in each of the two phases, the body will either float in the atmospheric ocean or emerge so that the visibility conditions of the Red Spot must depend on phase transition processes which occur in the floating body.

In order to maintain angular momentum during changes in depth, the body must either increase or decrease the rate of longitudinal drift, i.e., must change its rotation period in comparison with the surrounding cloud layer. Correspondingly the visible intensity of the Red Spot will be uneven and must be correlated in a specific way with the observed acceleration in the longitudinal drift of the Red Spot. Peek obtained correlation coefficient $r = +0.36$, which he considered significant, while considering the possible influence of other factors on the visibility of the Spot, including overlying cloud layers, etc. However the correlation coefficients, calculated not for the period from 1892 to 1947, but for the intervals 1893-1938 and 1939-1947 proved to have a different sign (in the second period r proved to be negative).

The considerations expressed by Peek were of a purely qualitative nature. Theoretical calculations were not accomplished which could have shown that the hypothesis of the floating body in fact satisfies all of the characteristics observed on the Red Spot. First of all, even without special calculations, it is easy to see that not one of the substances which can possibly be present in the Jovian atmosphere can be in a solid state throughout the entire depth of the Spot and at the same time provide for its buoyancy. In fact, the temperature and pressure at the surface of the cloud layer are insufficient for light gases (hydrogen or helium) to be in the solid phase. Heavier and more lightly condensed gases could not provide the low density required of the substance of the floating island.

Theoretical calculations were accomplished by C. Sagan [187] (who revealed / that the floating Red Spot could not always remain at the same latitude. On a rotating planet a spherical body with mass m, density ρ and radius r, floating at latitude ϕ in a non-compressible medium with density ρ_0 will be acted upon by Eotvos-Lambert force, which displaces the body toward the equator

$$F \simeq -\left(1 - \frac{\rho}{\rho_0}\right) m \frac{r}{R} g_0 \left(\frac{5}{2} f - e\right) \cos \varphi \,|\sin \varphi|, \qquad (5.16)$$

where g_0 is the gravitational acceleration at the planetary equator with equatorial radius R, e is the ellipticity (flattening) of the planet, $f = \omega^2 R/g_0$, where ω is the angular velocity of planetary rotation. The mean latitudinal displacement of the floating body during time τ amounts to

$$\varphi - \varphi_0 \simeq -0{,}17\left(1 - \frac{\rho}{\rho_0}\right) \frac{r}{R^2} g_0 \left(\frac{5}{2} f - e\right) \tau^2. \qquad (5.17)$$

Considering that during time τ > 130 years and if the Red Spot was shifted in latitude, then the value is $\phi - \phi_0 < 10°$ and assuming that $R = 7.14 \cdot 10^9$ cm, $r = 2 \cdot 10^9$ cm, $e = 6.2 \cdot 10^{-2}$, Sagan finds that

$$1 - \frac{\rho}{\rho_0} < 5 \cdot 10^{-24}. \qquad (5.18)$$

This means that the difference in the densities of the floating body and the surrounding medium must be vanishingly small, which is almost improbable. A larger difference in densities might lead to the same effect only in the case of a very viscous medium. However a contradiction then arises--in order to explain the observed longitudinal drift of the Red Spot it is necessary to assume a medium of low viscosity.

In the case of a two-phase model of the floating body, the effective density of the medium and the mean density of the body must be approximately equal. The mean density of the body changes as a result of phase transformation occurring within it. However with a change in this mean density and a shift of the limits of the phase transformation the effective density of the medium, with respect to the body, must also change simultaneously as a result of the ascent or descent of the entire body. Density increases with depth and, naturally, during submergence of the body the effective density of the medium must increase, while the difference in the mean densities of the body in the medium remain practically unchanged.

Changes in the level of the Spot required to explain longitudinal acceleration due to maintenance of angular momentum amount in all to several tens of kilometers. The sinking rate of the Red Spot is less than 1 mm/sec. All this leads to the fact that the latitudinal displacement of the Spot remains within the limits observed.

The physical nature of the substance and the reasons for phase transformations in such a two-layer island remain, nevertheless unexplained. /160

Recently Wildt and De Marcus [188] advanced a new hypothesis in agreement with which the Red Spot, not being a solid body, nevertheless represents a floating formation with a density equal to the density of the surrounding medium, but different from the latter by the phase of the matter. The fact is that certain three-component systems (for example, a mixture of hydrogen, helium and ammonia) at specific temperature and pressure values may disintegrate into two phases with equal densities, but with a somewhat different quantitative chemical composition. Then the appearance of the Red Spot may be examined simply as the result of thermodynamic processes in a multi-component mixture of heavily compressed or liquefied gases.

Another version is possible in two-component, two-phase systems when the phases differ in density. In this case, depending upon pressure and temperature, the sign of the difference in density of two phases may change, which in turn may lead to the development of hydrodynamic currents associated with the emergence of a lighter substance.

For the present a detailed discussion of this hypothesis is difficult since we do not know and only with a great amount of difficulty can imagine the real thermobarometric conditions in the lower atmosphere and on the surface of Jupiter.

b) The gas column hypothesis. The proposition that the Red Spot is a floating island was developed basically as a result of the necessity for considering the longitudinal drift of the Spot, which cannot be explained by associating the Spot with a specific region of the solid surface. It was assumed that the solid planet must rotate uniformly with a constant angular velocity. However this position cannot be regarded as indisputable for giant planets, considering their peculiarities in chemical composition and internal structure. The core and the mantle of Jupiter may not be linked firmly with each other and an exchange of angular momentum between the core and the mantle or between the mantle and the atmosphere is possible, leading to the appearance of torsional vibrations of individual shells of the planet. It is this proposal which was made by R. Hide [189,190], who had developed a hypothesis of the origin of the Red Spot, allowing for the hydrodynamics of a rotating atmosphere.

Let us imagine that a certain elevation or depression (Figure 65) is located on the solid surface of Jupiter. This formation certainly must create certain disturbances in atmospheric currents directed along the surface of the planet. Let U be the maximum typical velocity of horizontal currents, L be the horizontal characteristic of the length of the system of currents and Ω be the angular velocity of rotation. Then in the absence of significant non-uniformities in density and intensive friction effects, in agreement with /16 the Proudman-Taylor theorem, where $U/L\Omega \ll 1$, currents which do not change rapidly with time, i.e., which do not significantly change the value $2\pi/\Omega$, tend to be two-dimensional. This means that they tend to be disposed in the plane perpendicular to the axis of rotation. If this condition is applied to Jupiter then it may be understood that while flowing around a detail on the surface in the horizontal plane, the atmospheric currents on Jupiter will attempt to maintain this streamlined flow even at a rather high altitude above the detail, so that the hydrodynamic effect caused by the detail will be preserved even at the altitude of the limit of the cloud layer. The "transfer" of this effect from the lower levels of the Jovian atmosphere to the upper levels will occur in parallel to the Jovian rotational axis.

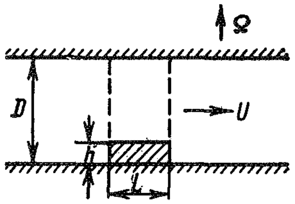


Figure 65. The Formation of the "Taylor Column."

In order to create the effect described, the vertical dimension (altitude or depth) of such a topographical detail must be not less than

$$h = \alpha (R_0 - R_m) \frac{U}{L\Omega}, \qquad (5.19)$$

where α is a number of order unity; $R_0 - R_m = D$ is the atmospheric depth. For Jupiter, if we accept $U \sim 10^2$ cm/sec and $L \sim 10^9$ cm where $\Omega = 1.7 \cdot 10^{-4}$ rad/sec, we obtain

$$h \simeq 10^{-3} D. \qquad (5.20)$$

Laboratory experiments accomplished by K. Titman [191] and R. Hide and A. Ibbetson [192] involving vessels with a rotating liquid reveal that such an effect of the formation of the so-called "Taylor column" above an elevation or a depression does actually exist (Figure 66). So far we do not know the depth of the Jovian atmosphere and therefore the vertical extent of the irregularity assumed on the Jovian surface may only be roughly estimated. If we assume that $D \simeq 10^8$ cm, we find that $h \geqslant 10^5$ cm, i.e., the altitude or the depth of the irregularity must be of the order of 1 km. In order to explain the uniqueness of the Red Spot Hide assumes that formations with smaller values /162
for the linear horizontal dimension are simply not capable of causing disturbances in the atmosphere.

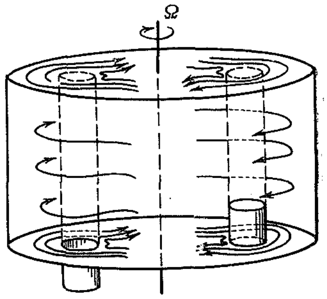


Figure 66. The Experiment of Titman in the Formation of a Taylor Column in a Rotating Vessel Containing Liquid.

The gas column hypothesis is very attractive. It is a good explanation of the apparent shape of the Red Spot, of its latitudinal stability and of its interaction with other cloud formations. In this connection longitudinal shifts in the Spot are linked with a non-uniformity in the rotation of the Jovian mantle, which is replaced by a moment of rotation with a liquid metallic core, in which, apparently, a variable magnetic field appears. Many problems in this hypothesis still require further development. Thus it is still not clear whether the conditions are actually fulfilled in the outer atmosphere of Jupiter which are necessary for the formation of the Taylor column;

or whether the atmosphere is in motion near the transition zone between the atmosphere and the mantle. Not exactly known is the role played by the effects of non-uniformity, compressibility and viscosity of the medium, as well as how the curvature of the planet influences the stability of the Taylor column. Appropriate rough calculations were accomplished by Hide, but since real conditions in the outer Jovian atmosphere are still completely unknown, these calculations cannot serve as proof of the correctness of the hypothesis. The causes are also not known for the appearance on the Jovian surface of a gigantic irregularity. S. Runcorn and J. Dickel presume that this may be a meteorite crater of comparatively recent origin.

If the surface of Jupiter is plastic such a depression may exist for a comparatively extended period of time. On the other hand it seems that the topographical detail must have an endogenic origin. Observed changes in the visibility of the Red Spot, its shape and coloration during the preservation of disturbances in the cloud layer, when the Spot is not visible, may be associated with purely atmospheric phenomena, but may also be caused by a certain unstable process in the release of energy from the interior of the planet in the region of topographic detail. In the latter case, for example, the temperature within the column may change while the column itself as a hydrodynamically stable formation is maintained.

§5. The Atmospheric Activity of Jupiter

a) Large-scale changes. Changes in the width, latitude, intensity and coloration of individual bands, which occur on the visible surface of the cloud layer, are apparently a reflection of rather powerful internal processes which react on the circulation of the atmosphere, if, of course, they are not associated only with the upper layers of the atmosphere and if they are not considered the result, for example, of a variable greenhouse effect. /163

For the present there is no real possibility of judging the nature of the sources of atmospheric activity which are not based on purely speculative considerations. Information which exists up to the present time concerning the active processes in the Jovian cloud layer is still far from sufficient to give a conclusive interpretation of phenomena observed. Therefore attempts are now being undertaken, although they are not yet too numerous, to reveal some kind of regularities in these phenomena, and in those changes which have been recorded on the Jovian disk, both visually and photographically.

The most easily determined quantity which characterizes the large-scale changes on Jupiter is the width of the basic dark bands. Particularly strong are changes in the width of the equatorial (tropical) bands, which may be seen from the graph (Figure 67). The width of both bands undergoes noticeable changes even in the course of 2-4 years. According to data in the work V. A. Bronshten, A. N. Sedyakina and Z. A. Strel'tsova [193], the amplitude of the changes in width amount ordinarily to 5-8°, but sometimes, as occurred, for example, in 1918-1920, it reaches 16°. The progress of change in the width of bands in various years is either identical or is of the mirror type--when the maximum of the width of one band corresponds to a minimum in another. A strict periodicity in changes has not been detected.

Attempts have been made to show periodicity in changes in the width of the bands through the use of harmonic analysis. R. Freitas Mourao [194] found a width change period for the north equatorial belt of approximately 4.5 years. E. Schoenberg and W. Heintz [195] found that changes in the width of the NEB and SEB may follow a period of approximately 11.4 years. According to J. Focas [196], changes in the width of the basic bands show the following periodicities, although they are not very clearly expressed: SSTB--12 to 15 years, STB--14 to 16 years, SEB$_S$--4 to 6 years, SEB$_N$--12 to 16 years, NEB$_N$--3 to 6 years, NTB--10 to 14 years. This reveals a certain cyclicity in changes of the widths of the bands, rather than a periodicity. It is difficult to judge changes in the widths of the bands, with the exception of the equatorial bands, since the majority of the bands appear to be narrow and their width is often unequal at various longitudes.

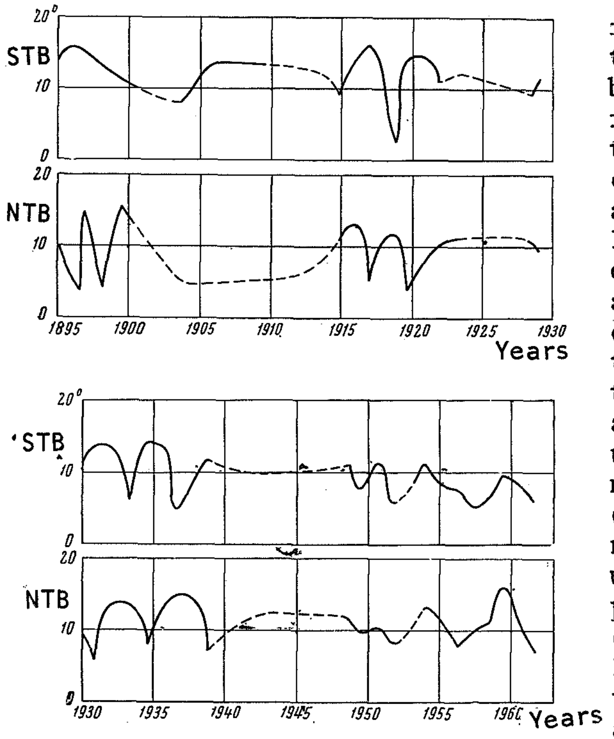


Figure 67. Changes with Time in the Width of Jovian Equatorial Bands.

It is quite probable that even further investigations of changes into the width and latitude of the Jovian bands will not lead to more specific results. The fact is that the width of the bands does not necessarily have to characterize uniquely the degree of activity of a given area of the planet. If the source (or sources) of the energy of processes which occur are situated at a great depth, then the release of dark band substance on the surface of the cloud layer must depend not only on the quantity of energy released, but also on the nature of circulation in the upper layers of the atmosphere, which /164 may depend not only on internal processes. Therefore the width of a band may be associated in a complex manner with changes in various atmospheric parameters. Then even with a periodic change in the quantity of energy released from interior layers of Jupiter, the width of the bands will change in a completely different manner. Of course, in this connection a certain regularity must exist.

In this connection we must not fail to devote some attention to recurrence periods in the overall appearance of Jupiter. Photographs of the planet made at times separated by intervals of decades appear to be almost identical, for example, photographs of 1915 and 1965. The distribution of bands, their width and even the relative intensity on such photographs are reproduced almost exactly. Would it be useful to search for a relationship in this specific recurrence period in the overall appearance of Jupiter? In any case first of all it is necessary to study the complete activity of the entire planet or of each hemisphere separately. With partial divergence in the /165 various circulation zones the state of the entire hemisphere of Jupiter must, to a rather definite degree, correspond to the release of internal energy. In this case it is necessary to search for such quantitative criteria in the condition of the visible surface of the Jovian cloud layer which might, in a definite manner, reflect the degree of atmospheric activity and its energy.

J. Focas [196] accepted the quantity of the dark substance on the Jovian disk as such a criterion. In examining the total activity of Jupiter by hemispheres for 1857-1961, he came to the conclusion that a 20-22 year cycle exists for the entire planet and that total activity minimums are subordinate to this cycle. During one cycle the activity in individual atmospheric belts, or circulation cells, may have one or two maximums. An inverse pattern was observed in the intensity of the activity in neighboring belts; if, for example, the STB was strong, then the SEB proved to be weak, and vice versa. The same relationship was also observed in the northern hemisphere. In addition, the impression is created that the beginning cycle of activity appears first of all at the higher latitudes and then the active processes reach the equator, after which they are again propagated toward the poles. The total intensity of the active processes is somewhat higher in the southern hemisphere than in the northern hemisphere.

b) The development of active regions. The dark Jovian bands, apparently corresponding to the more dynamic zones of its atmosphere, noticeably differ from each other at each moment by their turbulent structure, dimensions and shape of individual details and their motions. The regions where the most intensive processes occur, in agreement with the investigations of J. Focas, reveal their activity first of all by the appearance of sparkling, bright and dark substance in the form of individual spots and accumulations of spots. The bright zones of Jupiter reveal a certain weakly expressed structure of fine formations with dimensions of approximately 1". Bright white patches with dimensions of several arc seconds are present in disturbed regions.

The initial stage in the development of an active region, according to Focas, is of a cataclysmic nature. Individual bright spots appear, either individually or in whole groups. They are situated either in a limited longitudinal zone or in the entire active atmospheric cell, which corresponds to a specific latitudinal planetary belt. In a majority of cases the propagation of a disturbance in longitude occurs in the direction inverse to the rotation of Jupiter. The longevity of these spots varies from several days to several weeks.

The next stage consists of the appearance of dark nodes behind bright spots. The dark matter, as a rule, follows the bright matter. The dark /166 nodes serve as sources for the formation of dark filamentary currents, which move toward the poles and in the direction opposite to the rotation of the planet. In the final analysis they form the dark bands which in this period attained the maximum dark color. The time between the appearance of the bright substance and the formation of bands usually does not exceed one year.

The third stage is the appearance after the formation of bands of bright spots in the middle of the dark bands and at their borders. It is as if the bright substance pushes away the dark substance so that the bands become wider and the bright substance is situated along their axes. At the limits of the band the bright spots cause a curvature in the band outlines. Small dark bands divide the bright patches into individual segments.

The filaments which are released from the dark nodes are most clearly expressed in the equatorial and adjacent regions. Sometimes they represent connecting bridges which intersect the equator between one band and another. They are in motion, as Focas believes, at a higher level than the bands themselves. The filaments evolve slowly so that their longevity may reach a value of three months. The filaments remain visible even after the disappearance of the bright spots, in a period of attenuated activity. These consist usually of groups of dark spots which sometimes acquire a helical shape.

After the activity maximum the dark bands gradually disintegrate. Individual groups of dark spots disappear, the dark bands split, being divided longitudinally into two components first by the bright spots and then by an almost continuous bright band. The latter remain visible for an extended period of time, but are gradually weakened.

Such is the overall nature of the evolution of active regions on Jupiter. Similar phenomena occur at almost all latitudes, but their scale and intensity vary depending on latitude.

The longevity of cloud formations, according to the investigations of R. Falwell [202], who studied 176 individual cloud details on Jupiter, on the average equals 11.6 days in the equatorial region, 12.9 days in the south temperate belt and 10.8 days in the region of the Red Spot. Falwell associates the longevity of clouds in various zones with a radiation cycle, and finds that the longevity is approximately inversely proportional to radiation temperature; the longevity of clouds on Saturn t_s on the average equals 15.4 days, while the radiation temperature T_r of Saturn equals 78°K, so that

$$\frac{t_{s♃}}{t_{s♄}} \approx \frac{T_{r♄}}{T_{r♃}}. \tag{5.21}$$

This result must be considered as tentative, since cloud longevity must rather be associated with circulation and active atmospheric processes which /167 both on Jupiter and on Saturn are caused apparently not only and not so much by solar radiation, as by the release of internal thermal energy.

c) Photometric investigations of atmospheric activity. Photometric measurements of the distribution and relative quality of dark and light substance on the Jovian disk make it possible to obtain a quantitative estimate of the state of the cloud layer and of atmospheric activity. These evaluations may be compared both with other characteristics of the planetary cloud cover as well as with data concerning solar activity, the appearance of which in planetary atmospheres has not yet been studied at all. Insofar as Jupiter is concerned, as we shall see, the results thus far obtained are rather contradictory.

In analyzing a resume of visual measurements of the brightness of Jupiter, compiled by W. Becker [198] in 1933, B. M. Rubashev [167,168] detected that fluctuations in the brightness of this planet over a period of many years may be correlated with fluctuations in solar activity over a period of many years. Figure 68 shows curves of the brightness of Jupiter and the Wolf numbers plotted from sliding means derived for 10-year intervals. It is clearly apparent that the brightness of Jupiter is correlated with solar activity in that it decreases in periods of maximum solar activity and increases in periods of minimums in the secular cycle of solar activity.

Becker himself established the presence of a cycle of 11.6 ± 0.4 years in the fluctuations of Jovian brightness. However by means of the analysis of variance B. M. Rubashev revealed that the mean yearly values of Jovian brightness did not reveal a relationship with the phase of the 11-year cycle of solar activity. According to Beckers identical data, R. Shapiro [197] obtained a correlation coefficient of Jovian brightness with solar activity of $r = +0.374$, i.e., with an inverse sign of the value obtained from the comparison of the multi-year behavior, and with a value too small to testify to the presence of a real dependence.

R. Shapiro made photometric measurements of Jovian photographs obtained at the Lowell Observatory during a 17-year period of observations from 1926 to 1950. He investigated changes in the relative brightness of 18 individual latitudinal belts of Jupiter (with respect to the equatorial zone) in yellow and blue light. Average values obtained for the disk of relative brightness B, or rather, the values $(2 - 1/B)$ revealed a very high correlation with solar activity; in blue light the correlation coefficient equaled $r = +0.811$ for yearly mean Wolf number values and $r = +0.798$ for monthly mean values. In yellow light $r = +0.637$ and $r = +0.623$, respectively. In comparisons with an 11-year cycle of solar activity it is necessary to keep in mind that the rotation period of Jupiter around the sun is 11.85 years, i.e., it is very close to the average value of the solar cycle of 11.6 years. Shapiro calculated the correlation coefficient between the relative brightness and the heliocentric distance of Jupiter, but obtained $r = -0.459$. Reduction by distance led to a correlation coefficient between brightness in blue light and solar activity of $r = +0.804$. It thus appears that the relative brightness of the Jovian disk is associated with solar activity. In this connection it was shown that the correlation coefficient of relative brightness for higher latitudes with the Wolf numbers is higher than for lower latitudes. /16

Notwithstanding their attractiveness, Shapiro's conclusion regarding the close association of Jovian brightness with solar activity must be regarded as premature. The correlation obtained in the behavior of relative brightness and Wolf numbers proved to be accidental apparently due to an excessively limited time period in which the photographs of Jupiter were selected and processed.

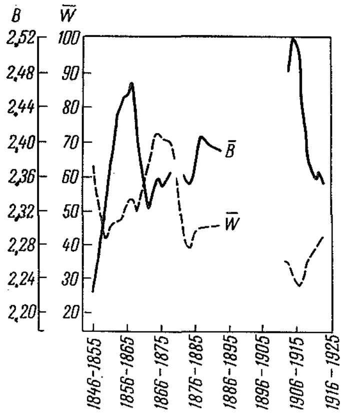


Figure 68. Change in Brightness of Jupiter B and in the Number of Sun Spots W according to a 10-year Sliding Mean (after B. M. Rubashev).

J. Focas [199] made photometric investigations involving photographs of Jupiter obtained at the Lowell Observatory by V. Slipher during the period from 1904 to 1963. The value of the so-called photometric activity coefficient was calculated; this coefficient was introduced previously by J. Focas and K. Banos [200] as a characteristic of the relative quantity of dark substance on the Jovian disk. If $I(\phi) = B(\phi)/B(0)$ is the brightness of a point on the central meridian of Jupiter with respect to the bright equatorial zone (ϕ is the zenocentric latitude), then the activity coefficient is found graphically from the photometric profile of the central meridian (Figure 69) or from the formula

$$R = \frac{1}{C}\int_{-45^\circ}^{+45^\circ} [1 - I(\varphi)]\, d\varphi, \tag{5.22}$$

where C is a constant equal to the area bounded by the limits of latitudes +45° and -45° and by line $I(\phi) = 1$. /169

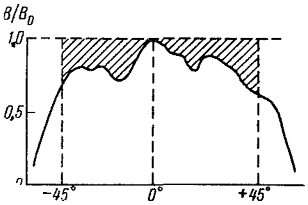


Figure 69. Graphic Determination of the Activity Coefficient.

The greater the dark substance on the Jovian disk, the higher the activity coefficient. Graphs of the change in the overall coefficient for the entire disk reveal the cyclic although not periodic behavior of value R (Figure 70), which in general does not follow the behavior of solar activity changes. However, in the period from 1928 to 1942, to which most of the photographs investigated by Shapiro pertained, the behavior of R and W proved to be identical. Correspondingly during this period there had to be high correlation coefficient values of relative Jovian brightness and Wolf numbers. However such an agreement was observed neither in previous nor in subsequent periods of time.

The measurements of Focas, nevertheless, are established on the basis of qualitative data concerning the existence of cyclicity in active processes on Jupiter. As shown by Figure 70 changes in the activity coefficient in the northern and southern hemispheres do not occur identically. If cycles occur in the southern hemisphere with intervals between mean maximums of 17-20 years, then these cycles occur less clearly in the northern hemisphere and the activity maximums occur every 6-11 years. In addition in the southern hemisphere there are two secondary maximums between the two main maximums, one of which ordinarily corresponds to the maximum in the southern hemisphere, and the second to the minimum.

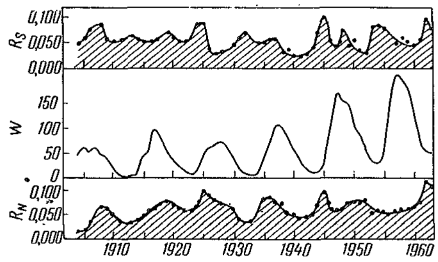


Figure 70. Activity Coefficient Change in the Northern (R_N) and in the Southern (R_S) Hemispheres of Jupiter and Wolf Number (W) Behavior (After Focas).

The quantity of dark substance in the northern hemisphere is usually somewhat greater than in the southern hemisphere, but the cataclysmic nature of activity is more sharply manifested in the southern hemisphere.

A photometric study of short-term changes in the activity of Jupiter was undertaken for the first time at the Astrophysics Institute of the Academy of Sciences of the Kazakh SSR by a group of investigators under the leadership of the author [201]. The magnitudes of the activity coefficient R for the entire disk and separately for the northern and southern hemispheres were determined based on 75 nights of observations during the period from August 1964 to March 1965 in five segments of the spectrum, isolated with light filters. Notwithstanding the rather wide spread in individual values R, a noticeable difference in activity in the hemispheres during this period was revealed (Figure 71), especially in green, orange and red light; individual fluctuations /170 in R in the northern hemisphere resulted in a cyclic behavior with a period of approximately 2-2.5 months, whereas in the southern hemisphere R changes very little and there is no cyclic behavior. The total quantity of dark matter in the northern hemisphere was greater than in the southern hemisphere. Cyclicity in the northern hemisphere appeared very weakly in blue and violet rays. It is possible that this is associated with one peculiarity in the condition of Jupiter during the period under consideration, i.e., a great part of the north equatorial belt was covered by an orange fog or haze which strongly absorbed blue and violet light; this probably explains the high values of R in these rays in the northern hemisphere. If the haze was situated higher than the main surface of the cloud layer subject to active processes, then it is possible that the active processes had little influence on the haze and it was therefore capable of remaining in a quiescent condition. In fact, in contrast to the NEB, which had a very broken southern border, the haze, visible, as a dark band in blue and violet light, had a completely even southern border.

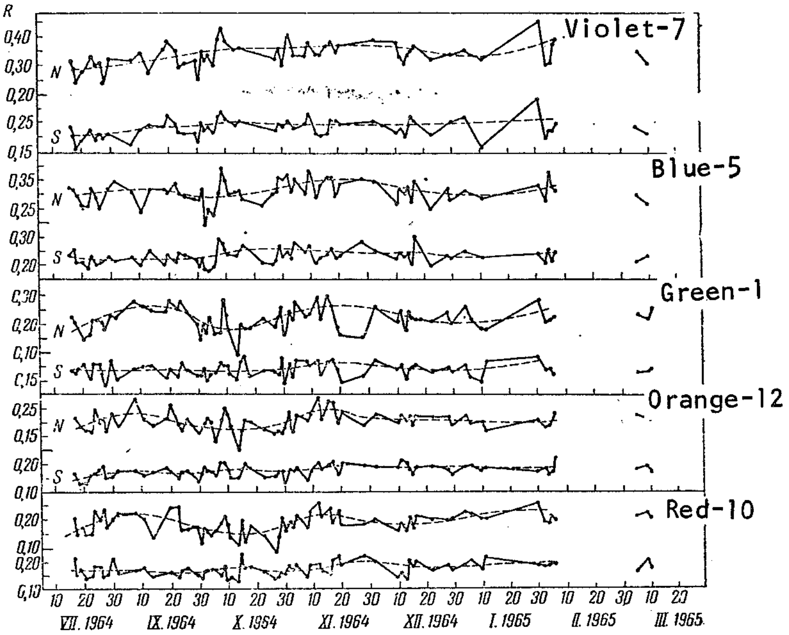


Figure 71. Short Periodical Changes in the Activity Coefficient in Various Colors in the Northern and Southern Hemispheres of Jupiter in 1964-1965.

The results cited certainly are of a tentative nature, although the presence of short-term periodic changes in the activity coefficient does deserve attention. In order to obtain reliable data concerning relationships in short-term periodic changes and bursts of atmospheric activity on Jupiter it is necessary to study phenomena on this planet just as phenomena occurring on the sun are studied, i.e., by means of a specially organized photographic service for Jupiter, to be accomplished in parallel fashion at several observatories situated at different geographical longitudes, and spaced as far apart as possible. The latter would permit observing Jupiter during the course of its entire rotation around its axis, which cannot be accomplished from one observatory. /171

d) Jovian atmospheric circulation and solar activity. The problem of the effect of solar activity on processes occurring in the planetary atmospheres presents interest not only for planetary physics, but also for geophysics, since any data concerning the presence of solar-planetary relationships supplements in an independent manner our information concerning the phenomena of solar activity on the earth. It is completely obvious that with an increase in distance of a planet from the sun the degree of effect of solar radiations on the state of the planetary atmosphere must decrease. Apparently however we cannot simply assume that this decrease is proportional to the square of the distance, or in other words we cannot maintain that the effect of solar activity on the Jovian atmosphere in all cases must be 27 times less than its effect on the earth's atmosphere. It is also necessary to consider the dimensions of the planet, the mass of its atmosphere and the presence of magnetic fields and radiation belts.

Unfortunately at the present time our information concerning solar activity phenomena in planetary atmospheres is very sparse and is not always based on completely reliable data. The main item is still lacking and that is uniform and completely objective observational material which encompasses an extended period of time or enough to permit us to investigate all short-term changes and solar-planetary relationships during a short time interval with a sufficient number of observations. We have already seen that a limited period of observations may lead to an erroneous conclusion concerning the role of solar activity in the Jovian atmosphere.

Several authors are now examining the possibility of the photochemical effect of solar ultraviolet radiation on the upper atmospheres of the planets [204,205]. However there are still no observational data in this connection. Very careful investigations of molecular absorption in the Jovian atmosphere are necessary in order to clarify possible changes in the apparent content of, for example, methane and ammonia associated with changes in the flow of ultraviolet and corpuscular radiation of the sun.

Atmospheric circulation is one of the most probable and most easily studied /17
types of manifestations of solar activity on the planets. The presence of solar-terrestrial correlation in the atmospheric circulation of our planet leads to the concept that dynamic processes occurring in the Jovian atmosphere, which are manifest in the different rotation rates of individual cloud zones and bands, may be associated with solar activity, if even to a small extent.

Attempts to find such relationships have been made repeatedly, but with quite limited material and without the application of specially developed analytic methods for solar-geophysical investigations. Attempts to find a correlation between short-term changes on Jupiter and solar activity in the final analysis did not lead to positive results. However success was obtained in detecting a relationship between the zonal rotation velocities of Jupiter and fluctuations in solar activity over a period of many years. An investigation of such a relationship was accomplished by B. M. Rubashev. A detailed description of his results is contained in his articles and monographs [167,168]. Here we shall enumerate the basic conclusions of this investigation.

The relationship was studied between the 10-year sliding mean values for the rotation periods of details in various latitudinal streams of Jupiter and the corresponding values for sliding mean Wolf numbers during the period from
1900-1939. The use of sliding means decreases the amplitudes of short-term /173
periodic fluctuations and more clearly reveals the long-term behavior of the values considered. Figure 72 shows graphs of the change in the solar activity and in the rotation period of a number of Jovian atmospheric currents. The rotation periods of the north tropical, south equatorial, south temperate and the south high-latitude (arctic) currents, as well as those of the south tropical disturbance, in long-term changes display in general a positive cor-

relation with long-term fluctuations in solar activity, i.e., the higher the long-term level of solar activity, the longer the rotation period of a given zone (the velocity is reduced). The north equatorial current and to a certain extent the Red Spot reveal a negative correlation of the long-term values of rotation periods with solar activity, i.e., their rotation rate increases with an increase in solar activity.

The relationship of the long-term period fluctuations with the curve of the "secular" cycle of solar activity is most clearly displayed in the south equatorial currents. It also reveals maximum amplitude of changes in the rotation period--up to 52 sec judging by initial data and approximately 25 sec according to sliding means. In certain cases replacement of the positive correlation by a negative correlation is observed (in the south tropical current) as well as behavioral changes in individual time intervals which do not correspond to solar activity behavior. Such changes were considered by B. M. Rubashev to be analogous to those which occur in the circulation behavior of the earth's atmosphere.

Interpretation of the results cited would still be premature. The period of observations utilized for comparisons (40 years) is all too short to arrive at completely definitive conclusions concerning the nature of the dependence of Jovian atmospheric circulation on solar activity.

In 1964 M. V. Kushnir-Ivanovskaya and B. M. Rubashev [203], using observational data of Jupiter for the period 1879-1948, again showed that the long-term behavior of the rotation periods of various zones of Jupiter parallels the behavior of the long-term values of Wolf numbers for the south branch of the equatorial current, for the south temperate, north temperate and south arctic currents (the zonal circulation is weakened with an increase in solar activity) and is inverted for the north branch of the equatorial current and for the north arctic current (the zonal circulation is increased with an increase in solar activity). The south branch of the equatorial current and the north arctic current show a shift from a parallel relationship to a mirror relationship in 1911-1917 and especially in 1932-1937. Disruptions also occurred in the "solar-terrestrial" relationships in the 1930s. For example, about 1935 the dependence of the number of days with intensive cyclones in arctic seas on Wolf numbers changed from a direct to an inverse relationship.

Conclusions

Notwithstanding the rather large quantity of observational information /174 obtained up to the present time by means of various methods of investigations, our concepts concerning the structure of the Jovian atmosphere, especially concerning its lower layers, its dynamics and the causes of intensive processes observed on the visible surface of the cloud layer are still quite indefinite. Further serious investigations are required, both observational and theoretical, so that the physical nature of this gigantic planet of the solar system will cease to be a riddle.

The majority of the results of investigations of Jupiter enumerated in this book must be regarded as tentative, since they are based, as a rule, only on sporadic observations and thus do not make it possible to follow changes in certain characteristics of the Jovian atmosphere. Therefore in the near future most of our attention must be directed toward the study of the different nature of variable phenomena on Jupiter. These include not only visible changes on the surface of the cloud layer, detected visually or photographically, but also changes in the parameters of the outer atmosphere and the cloud layer detected by spectral and photometric methods, temperature change changes with time over the Jovian disk, changes in the rotation rate of the outer atmosphere, fluctuations in the altitude of the cloud layer, etc.

We shall enumerate the basic prolems in the study of Jupiter in the near future by means of earth-based observational methods.

1. Photographic investigations of circulation processes in various latitudinal belts of Jupiter and a study of the dynamic characteristics of individual cloud formations.

2. Spectroscopic searches and the study of anomalies in the rates of motion of gas masses in the outer atmosphere according to planetary absorption lines.

3. A photometric study of Jovian atmospheric activity by hemispheres and by individual circulation cells (belts), and a study of the distrubution and development of active regions.

4. Spectrophotometric searches of absorption bands of chemical compounds, the presence of which are possible in the Jovian atmosphere.

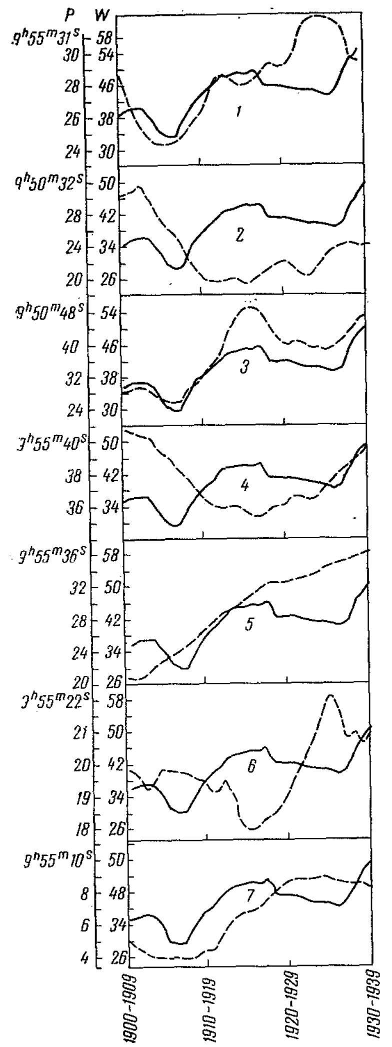


Figure 72. Graphs of the Change in Rotation Periods P of Various Jovian Zones (The dashed line) and in Solar Activity W (Continuous line) in Accordance with a 10-Year Sliding Mean (After B. M. Rubashev). 1, North Tropical current; 2, North equatorial current; 3, South equatorial current; 4, Red Spot; 5, South tropical disturbance; 6, South temperate current; 7, South arctic current.

5. A clarification of data concerning the quantitative chemical composition of the atmosphere with consideration for the role of multiple scattering in the cloud layer in the formation of absorption lines and bands.

6. A determination of optical parameters (optical thickness, reflectivity, scattering factors and continuous true absorption, scattering indicatrix) of the outer atmosphere and the cloud layer by means of photometry and spectrophotometry and an investigation of changes in these parameters with time and as a function of the radiation cycle of various planetary zones.

7. An investigation of the structure of the surface of the cloud layer and of the stratification of individual cloud belts and details by means of careful photometry of the disk and according to the intensity of molecular absorption bands.

8. A detailed investigation of radiometric temperature distribution on the Jovian disk, especially near the limb regions and near the terminator at maximum phase angles. It is especially important to accomplish such investigations in narrow segments of the radiometric "window" 8-14 μ and to obtain spectral radiation curves of individual planetary zones in this wavelength region.

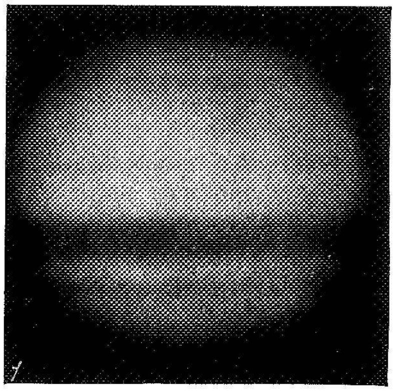
9. A determination of pressure and temperature at the surface of the cloud layer according to the intensity of rotational lines in molecular absorption bands.

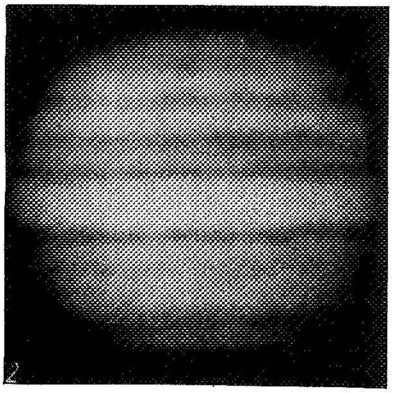
10. Theoretical calculations of models of the vertical structure of the Jovian atmosphere, its radiation cycle and a clarification of the possible role of the greenhouse effect.

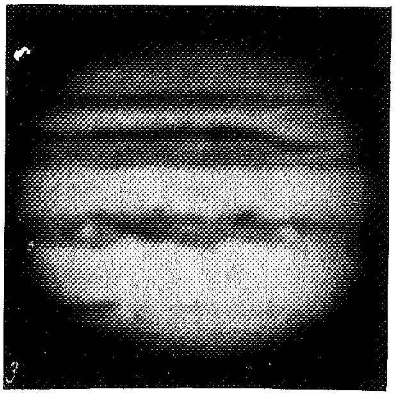
11. The development of a hydrodynamic theory of the overall circulation of the Jovian atmosphere.

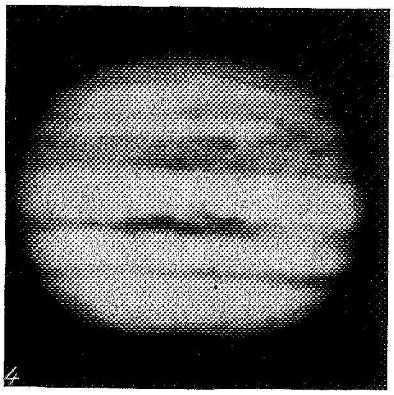
12. An investigation of the nature of sources of non-thermal radio frequency radiation of Jupiter and the possible relationship of these with processes on the visible surface.

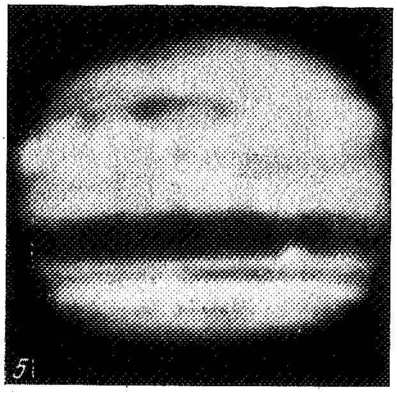
13. A theoretical examination of the problem of the nature of the surface (solid or semi-liquid) which lies in the zone of the first abrupt change in density under the Jovian atmosphere, and an examination of the nature of internal sources of heat and the role of the magnetic field of the planet in processes occurring in the lower layers of the atmosphere.

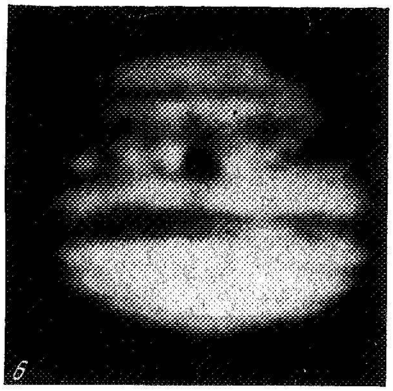




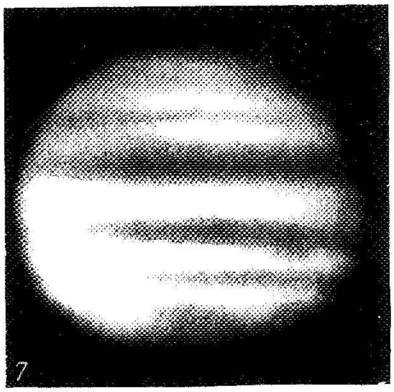


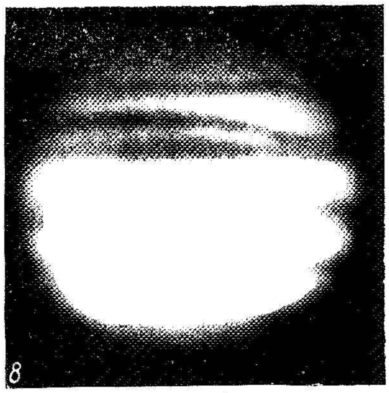


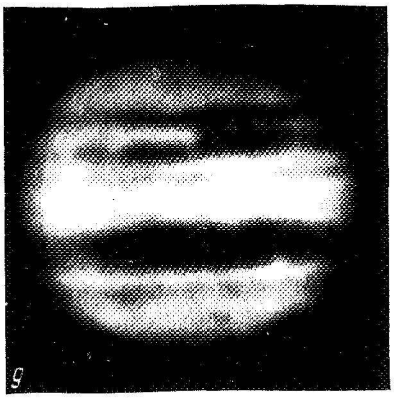


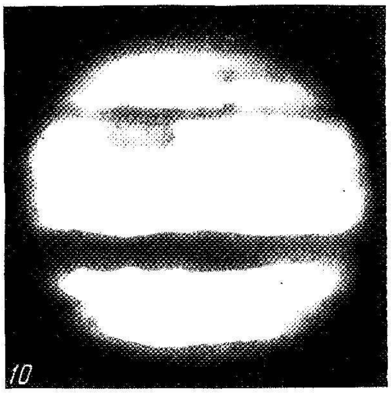


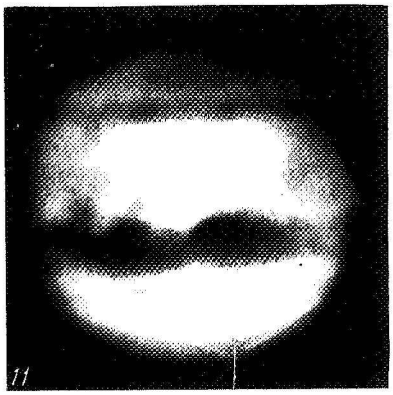
1. 2 December 1904.
2. 27 April 1909
3. 20 October 1915
4. 20 December 1917
5. 7 October 1928
6. 24 November 1928

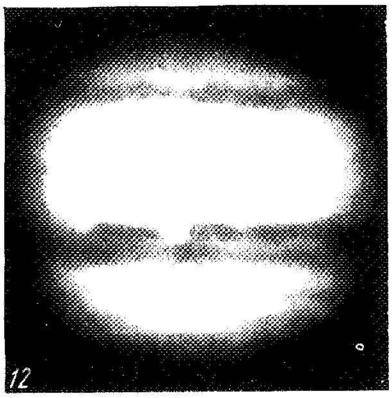




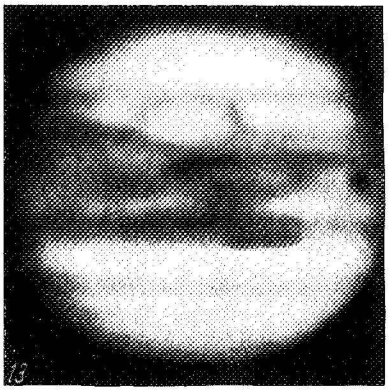


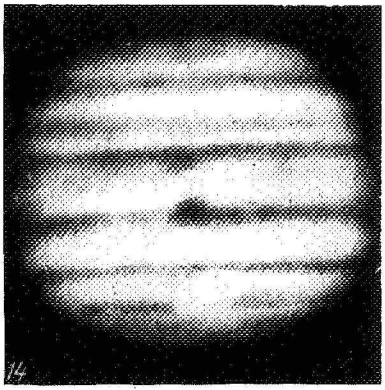


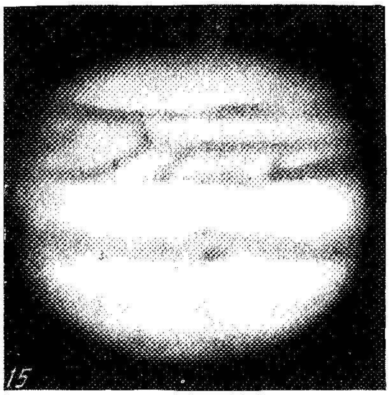


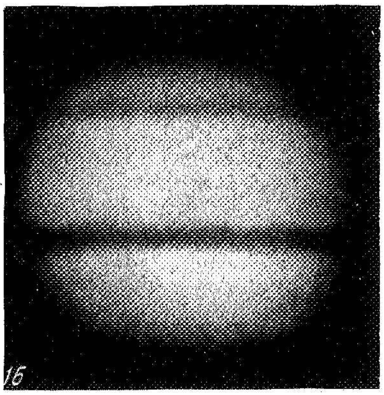


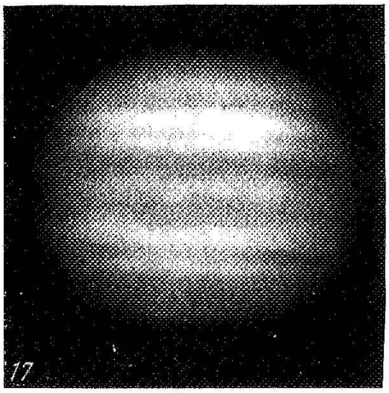
7. 31 January 1930
8. 18 February 1931
9. 27 April 1933
10. 5 July 1936
11. 15 June 1937
12. 16 July 1937

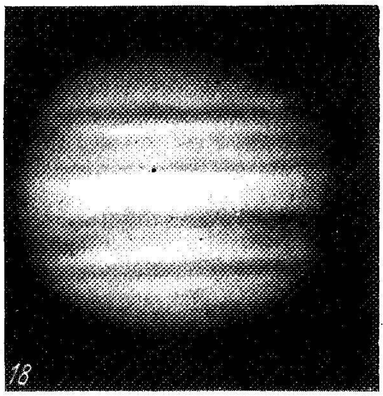












13. 11 August 1938
14. 26 August 1939
15. 8 June 1948
16. 9 October 1952
17. 13 November 1964
18. 13 March 1967

Judging from published accounts Jupiter will become an object of study in a program of space investigations, beginning around 1970. At first glance it apparently is difficult to anticipate any essential addition to our information concerning this planet from data obtained by space probes, although even the transmission of a television image of the planet from a close distance would present a tremendous amount of interest for the study of the structure of the Jovian cloud cover. With time however it will probably be possible to accomplish even continuous investigations of processes on Jupiter by means of orbital stations. The maximum interest may be presented by the study of /176 Jupiter from a close distance in those ranges (optical and radio astronomical) which are inaccessible to investigation from the surface of the Earth. Direct probing of the Jovian atmosphere would also be of tremendous value, although for the present it is difficult to say to what depths such probing could be accomplished while maintaining the capability of transmitting the information to the Earth.

In any case Earth-based investigations of Jupiter will not lose their value for at least several decades, until manned space vehicles are directed toward Jupiter.

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